Electronics for Big Scientific Instruments
ATLAS HEC and VLT Telescope

Universidad de Málaga – 20.04.2015

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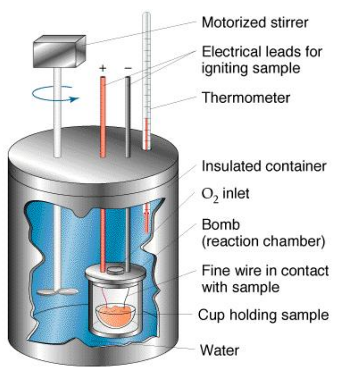
Outline

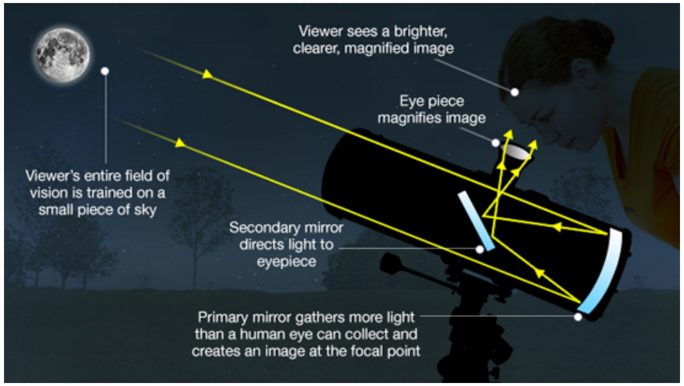
- **Notion of scientific instrument**
- **Big instrument electronics:** temperature, radiation, reliability, robutness (fault tolerance), obsolescence issues

- **ATLAS Hadronic Endcap Calorimeter (MPI fuer Physik):**
  - HEC front-end cold electronics: low noise front-end cryogenic amplifier
  - Device characterization: temperature and radiation
- **Very Large Telescope (European Southern Observatory):**
  - Adaptive optics wavefront sensor
  - Obsolescence: motor controller
  - CRIRES+

Scientific Instruments

- Equipment or apparatus
- Apply physical principles and technology to acquire, process and storage physical variables.
- Purpose: measuring, testing, viewing, detecting, recording, analysing, inspecting.
- They may be (and in fact they are) part of laboratory equipment.
- More sophisticated than simple scales (altimeter, oscilloscope, thermometer, oscilloscope)



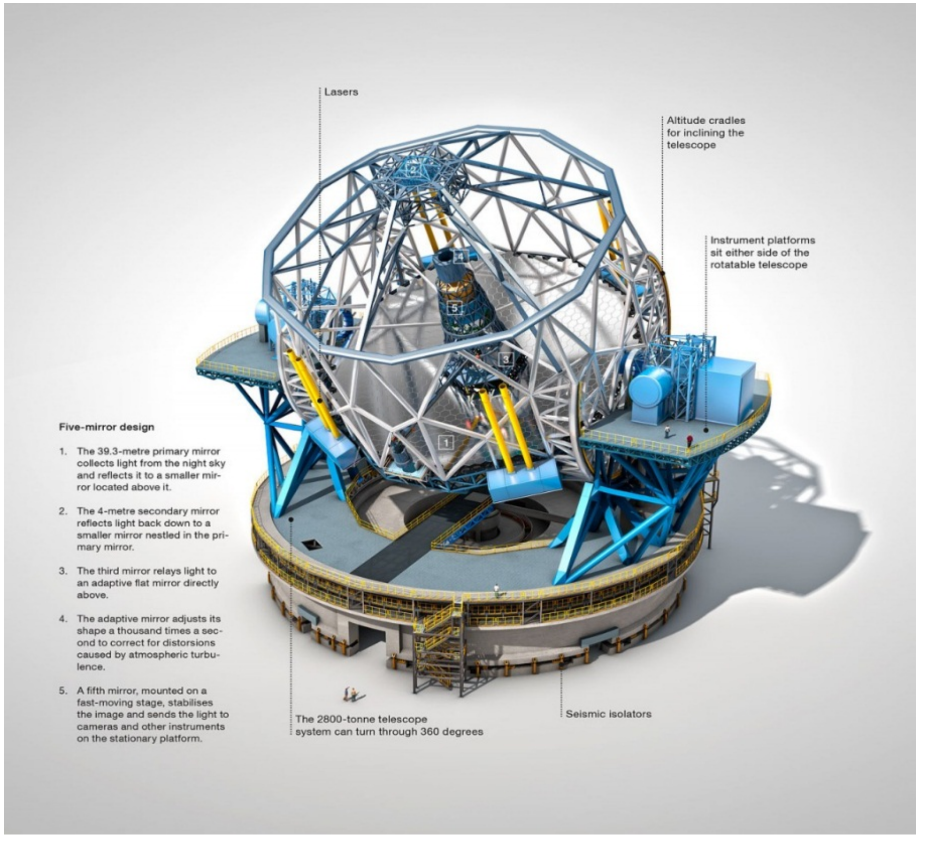


Calorimeter

Telescope

Big scientific instruments

- A scientific instrument can be found at nanoscale (non-invasive imaging, nanorobots) or…
- Weight tons, be huge in size and technologically complex:
  - Particle colliders (miles)
  - Telescopes and radio-telescopes antennas, antenna arrays (astrophysics).
- Face latest physics challenges
- Components:
  - Mechanical
  - Optical
  - Electronic
  - Software
- Collaborative efforts:
  - Scientists
  - Engineers
  - Public and private funds
  - Partnerships, consortia

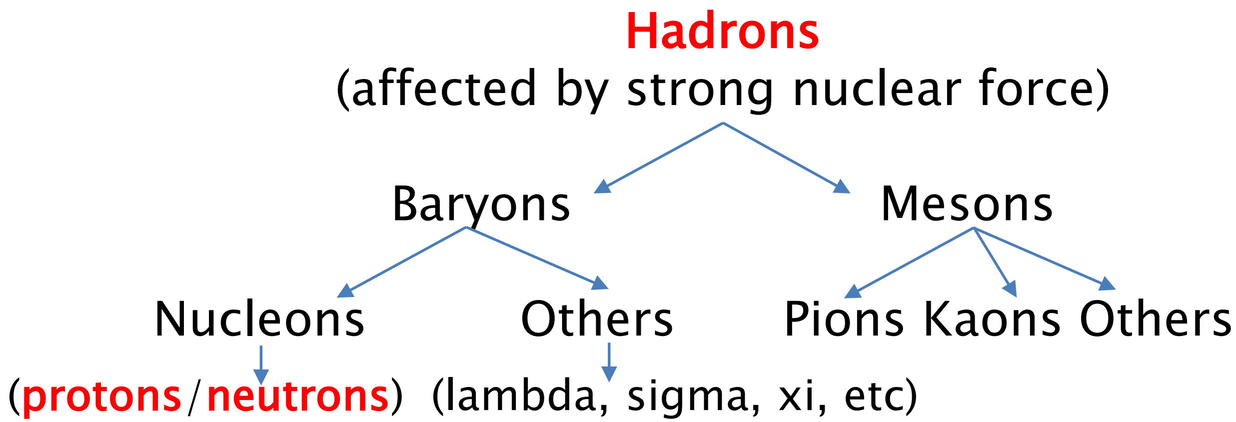


Electronics complexity

- Requirements:
  - According to scientific specs
  - Management: board committees
- Technical challenges:
  - Extreme environments:
    - Temperature: very high, very low (cryogenic) or large gradients.
    - Irradiation levels: space, on Earth (colliders).
  - Lifetime: obsolescence
  - Reliability: trustability, repetibility
  - Robutness: fault tolerance
  - Design for reuse

The ATLAS Hadronic Endcap Calorimeter

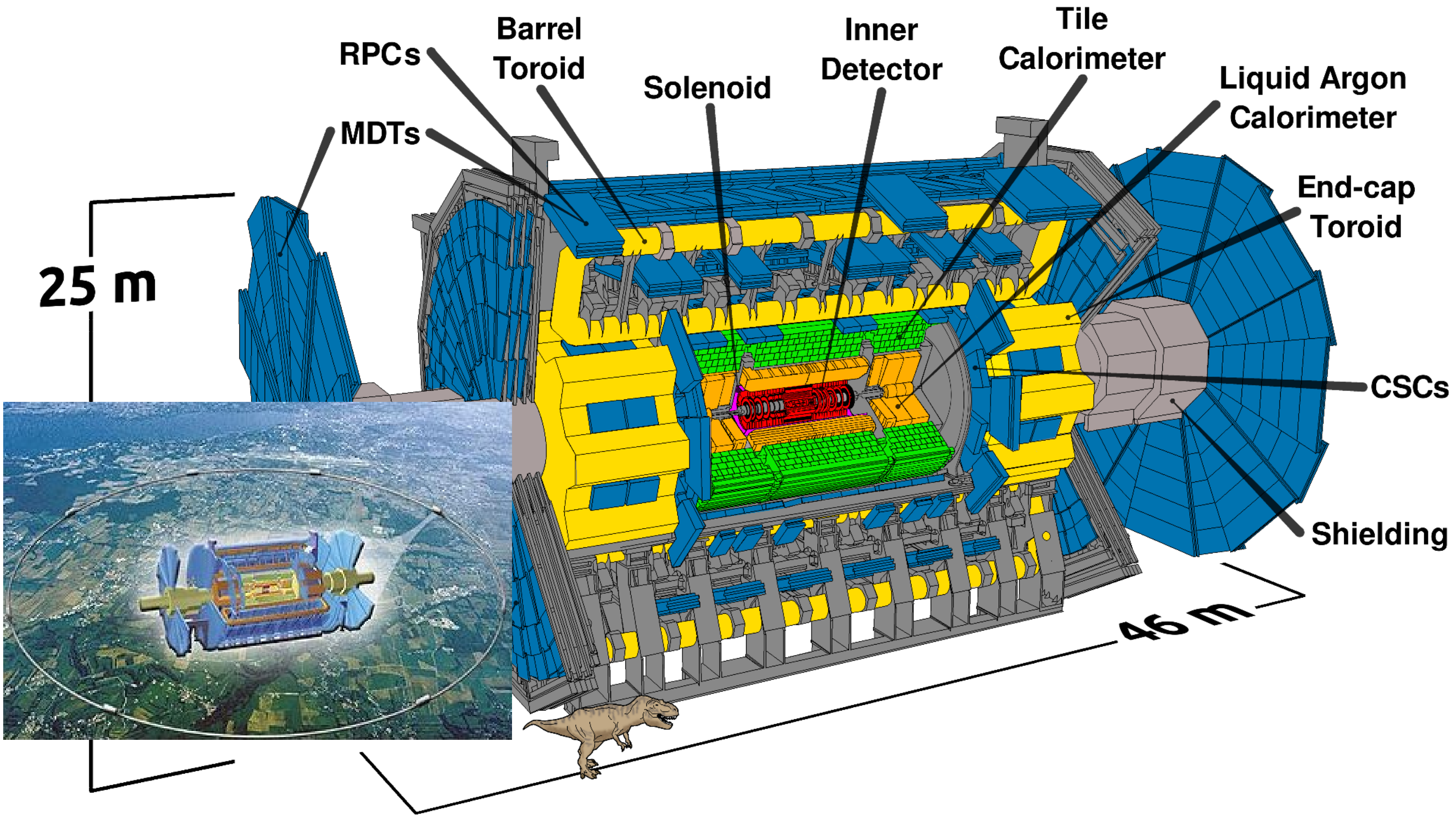
- LHC: Large Hadronic Collider (27 km in circumference, 175 m deep)
- Hadrons are made of quarks and held together by the strong force!



- ATLAS: **A Toroidal LHC ApparatuS**
- HEC: Hadronic Endcap Calorimeter

- ATLAS:
  - One of the five particle detectors (besides to ALICE, CMS, TOTEM y LHCb) of the LHC
  - 45x25 m and about 7000 tons
  - Around 2000 scientists involved and engineers of 151 institutions from 34 different countries

LHC and ATLAS main parts



http://hedberg.web.cern.ch/hedberg/home/atlas/atlas.html

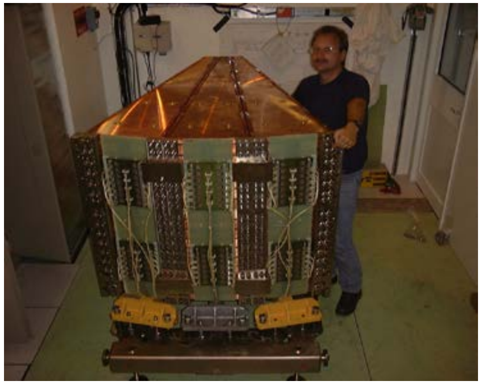
MPI fuer Physik

- Founded in 1917 as the Kaiser-Wilhem Institut für Physik, with Alber Einstein as first director
- After the second world war: to Göttingen (Max-Plank Institute für Physik, Werner Heisenberg)
- Moved to Munich **since 1958**
- High energy physics and astroparticle physics
- Experimental and theoretical physics

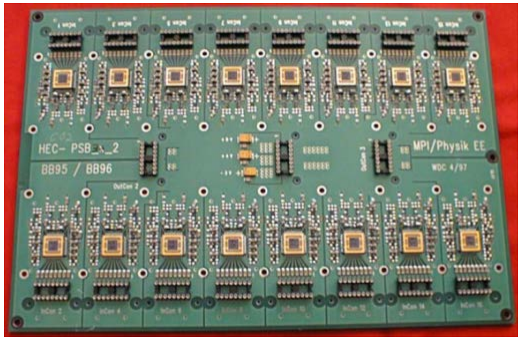
- Electronic department:
  - ATLAS MDT
  - ATLAS HEC
  - Magic Telescope (La Palma, Spain)
- Electronics Infraestructure:
  - PCB poputation, assembly
  - ASIC Bonding

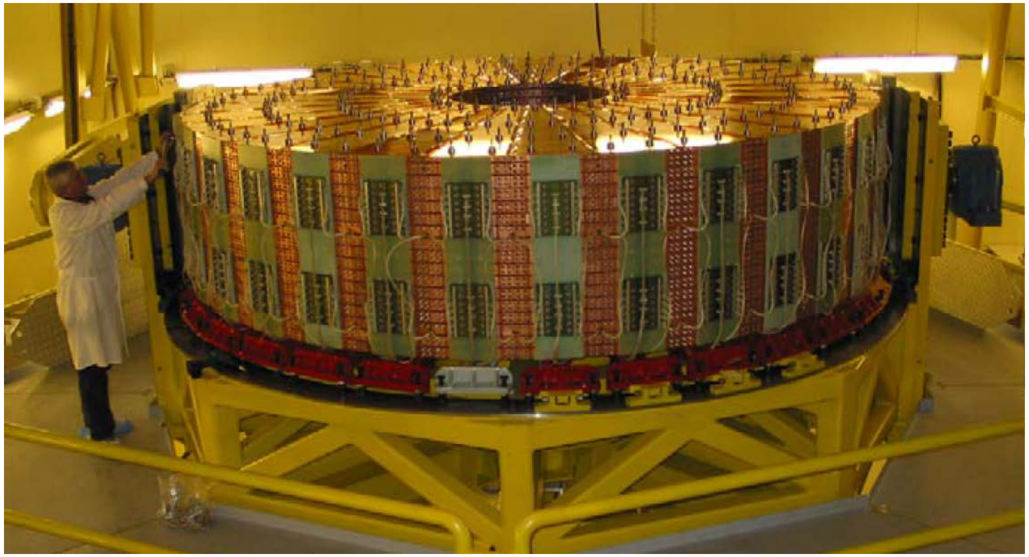
https://www.mpp.mpg.de

ATLAS HEC



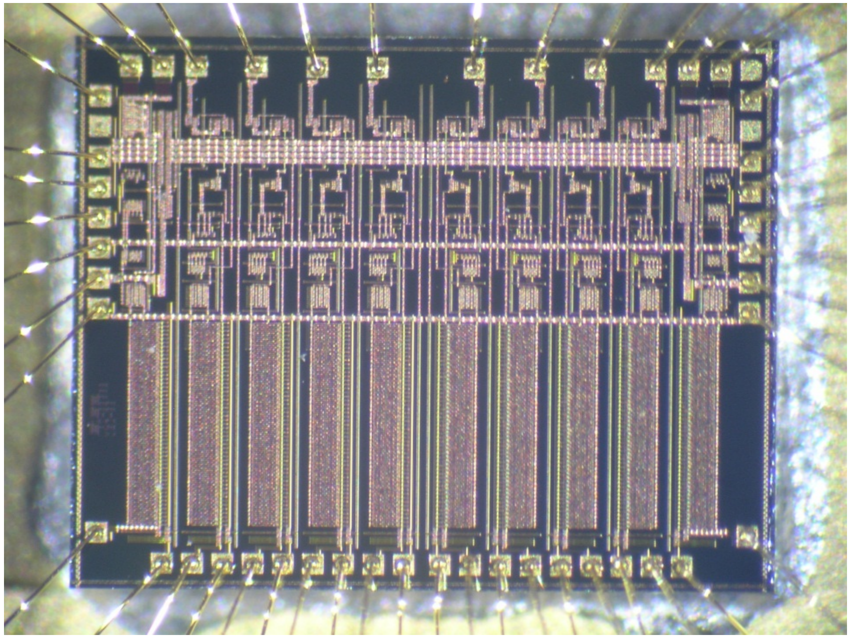
- Employes LAr (it becomes radioactive) and copper.
- Readout electronics:
  - Collision energy -> electrical current (pulses) to be amplified
  - Cryogenic and radiation-hardened
  - Low noise
- ASICs (GaAs) designed at the Max-Planck-Institute (MPI) fuer Physik (Munich, Germany). But only at a schematic level!
- Designed in 1996, produced in 1999, tested until 2002.
- PCB assembly and assurance tests at MPI.
- 20 boards from the preproduction batch extensively tested in cold and under radiation.

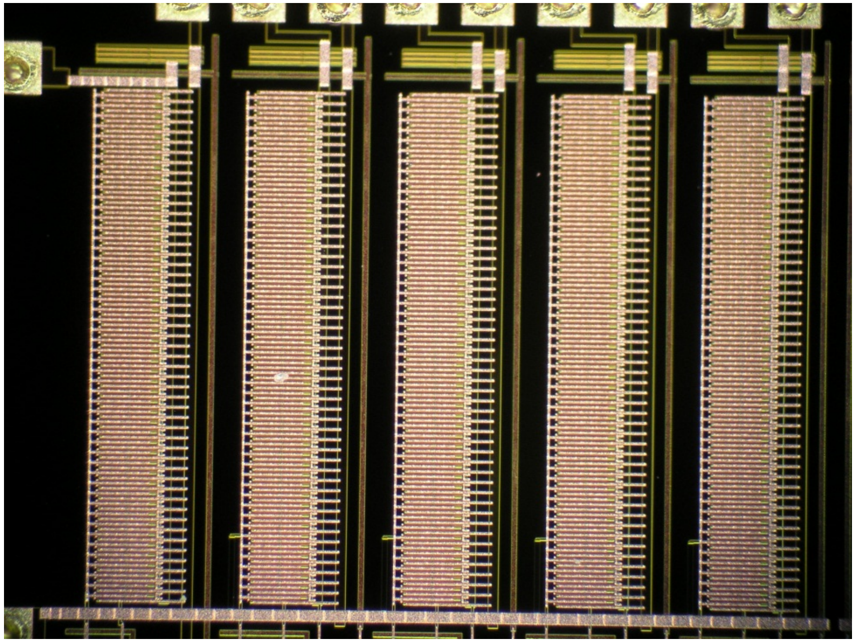




BB96 ASIC

- GaAs (TriQuint)
- JFET transistors
- Architecture: basic cascode stages
- Very large (wide) input transistors: high gain, low noise





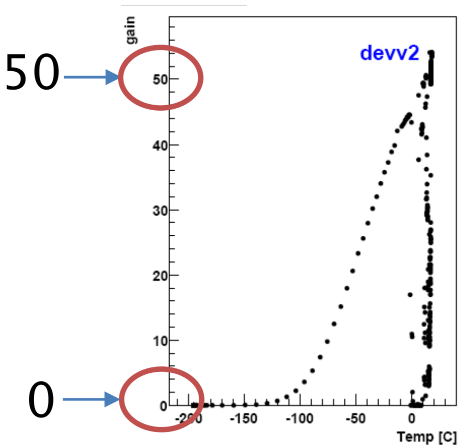
ATLAS HEC electronics update

- Radioactive LAr: defect PCBs cannot be replaced at all!
- Irradiation levels much higher than in space
- Design must guarantee 10 years lifetime
- Super-LHC (sLHC) was foreseen for 2016-:
  - Upgrade of accelerator and experiments
  - 10 times higher radiation background
  - New readout system foreseen for LAr
  - Radiation Hardness for HEC (for 10 years at sLHC):
    - Neutrons: $1,5 * 10^{15}$ n/cm^2
    - Photons: 50 kGy (kilogray = 1000 J/kg)
    - Protons: $1,2 * 10^{12}$ p/cm^2

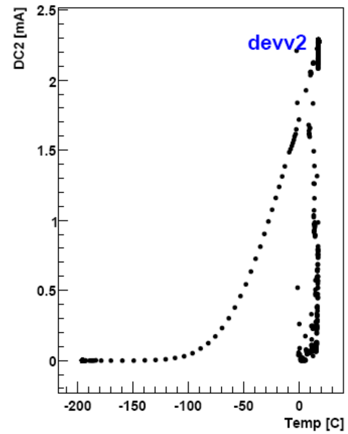
- In 2008 the preparation of new readout electronics started
- The old GaAs tech was no longer available
- New approcah: new technology and fully design the new ASIC at the MPI

HEC update, technology selection

Gain vs. Temp

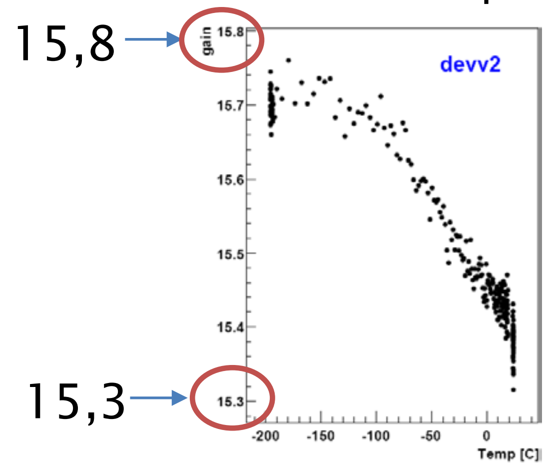


Ic vs. Temp

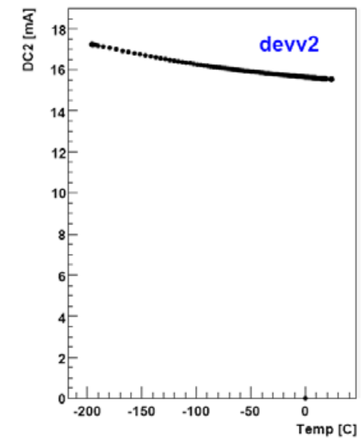


BJT: 100% gain change
(w/o temp. stabilization)

Gain vs. Temp



Ic vs. Temp



NMOS FET: 2% gain change
(w/o temp. stabilization)

Soft criteria

Future availavility
Cost
Support on design phase

Hard criteria

Gain (gm/Id)
Dynamic range / Linearity
Bias / power consumption
Frequency respose
Noise

Dependence on

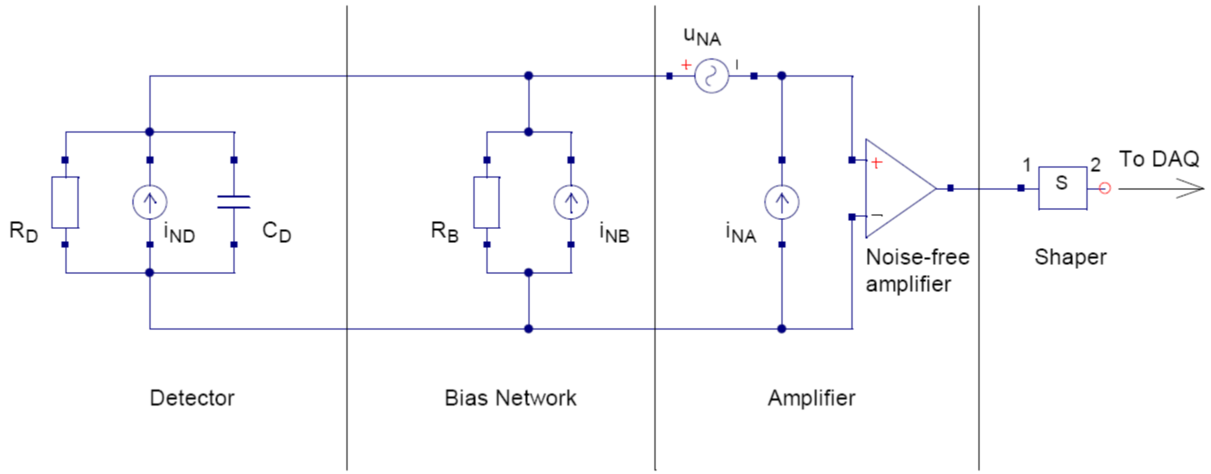
Radiation (neutrons, protons, gamma)
Temperature (cryogenic, room temperature)

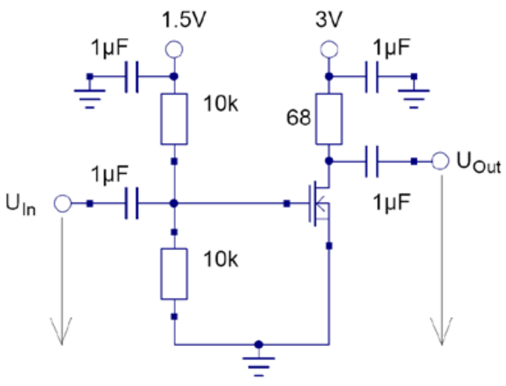
↓

SGB25V (CMOS 0,25 um) from IHP (foundry): `www.ihp-microelectronics.com`

IHP MOSFET Noise characterization

- HEC amplifier: front-end electronics after detector.
- It conditions whole chain noise performance → need for a Low Noise Amplifier (HEC-LNA).
- HEC-LNA performance will degrade over time under radiation and noise impacts sensitivity (Minimun Detectable Signal, MDS) → Dynamic range might be compromised.
- Need for cryogenic noise measurements automotion.





u_{NA}, i_{NA} mainly uncorrelated, some correlation may exist

Noise test bench (preliminary)

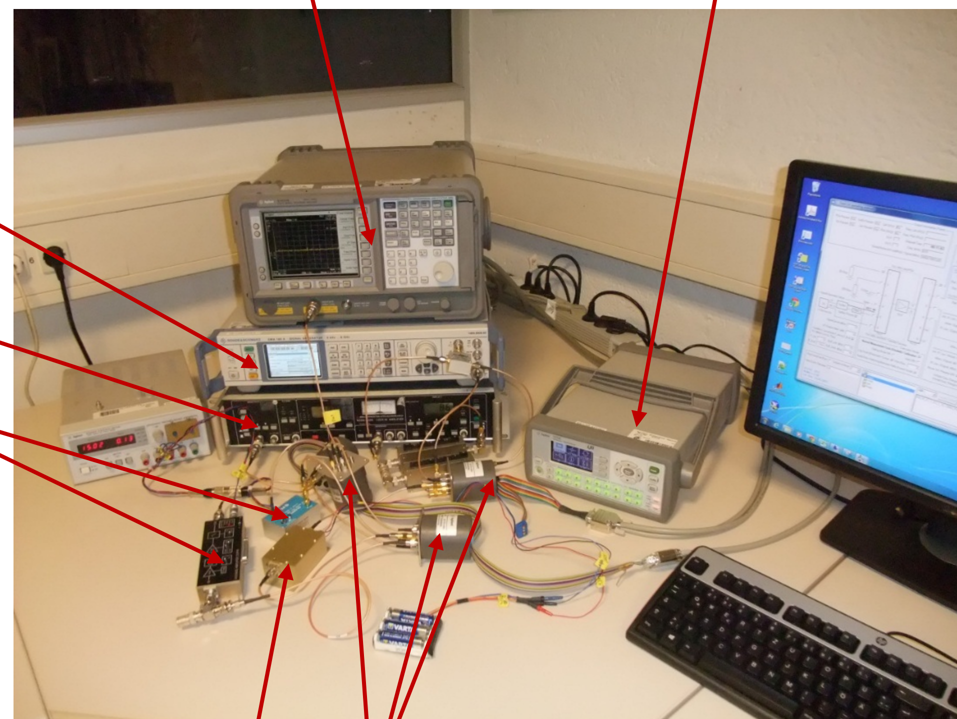
PSAs (R&S FSU, Agilent E440B)

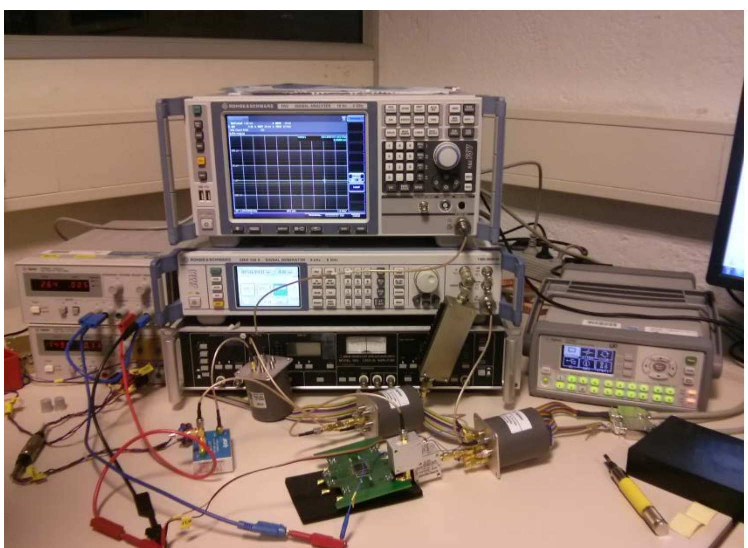
RF coaxial switches (driver)

Signal generator

Lock-in Amplifier (LIA)

Low-noise preamps (LNAs)

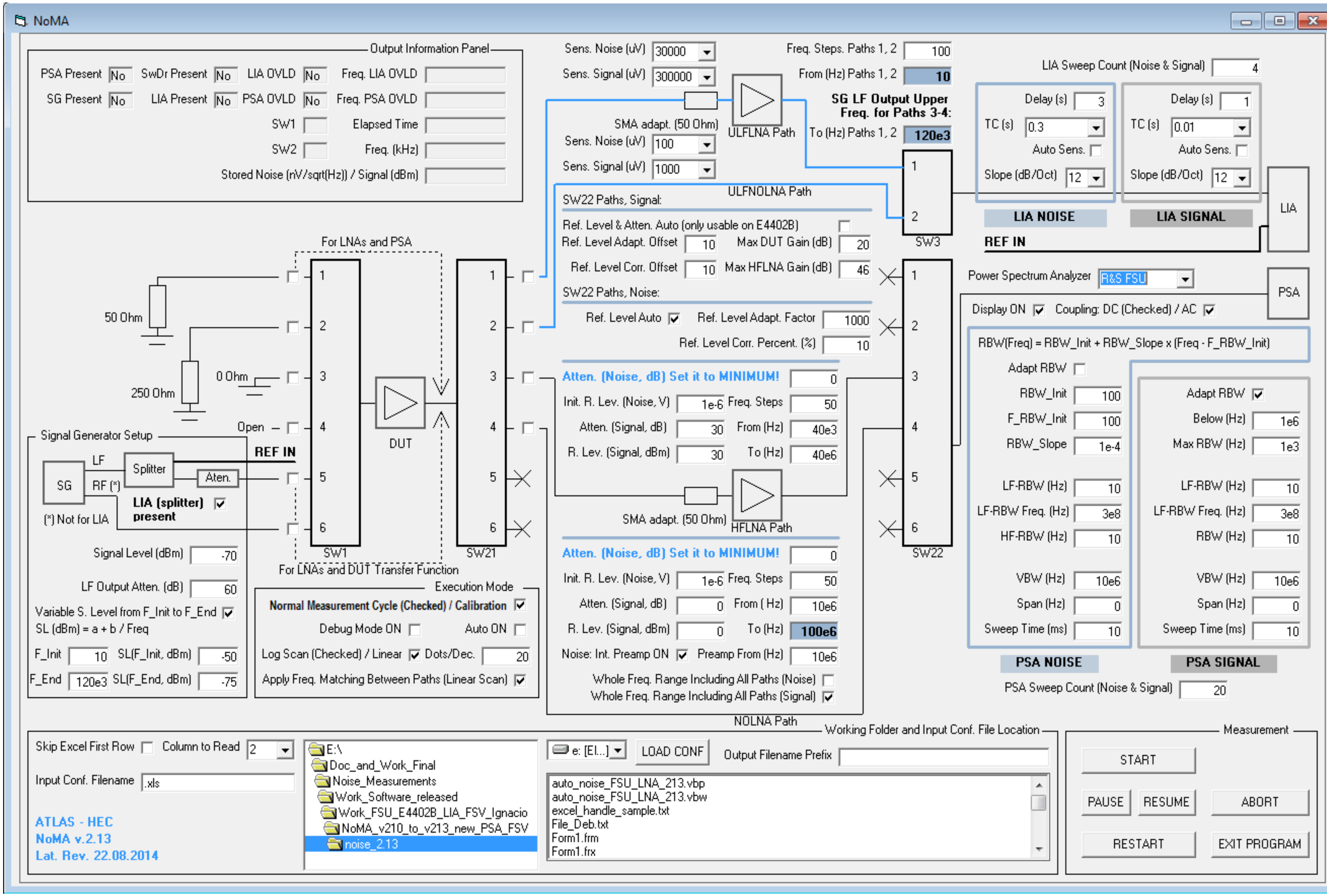




RF coaxial switches

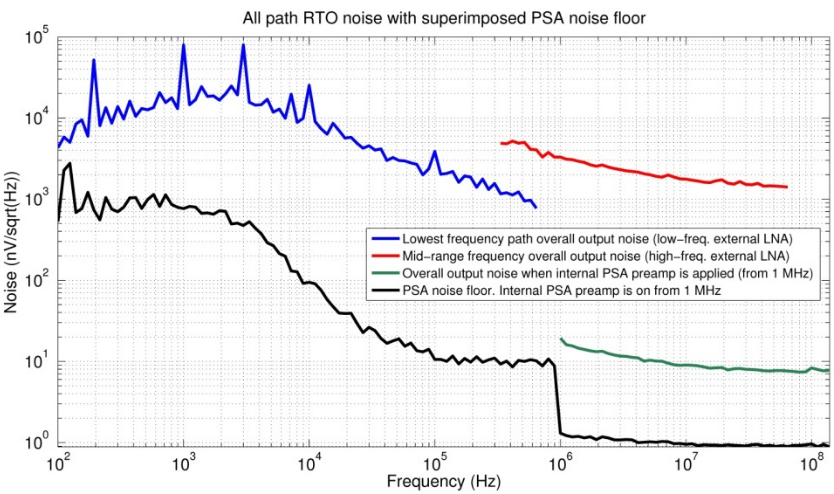
DUT (transistor sample)

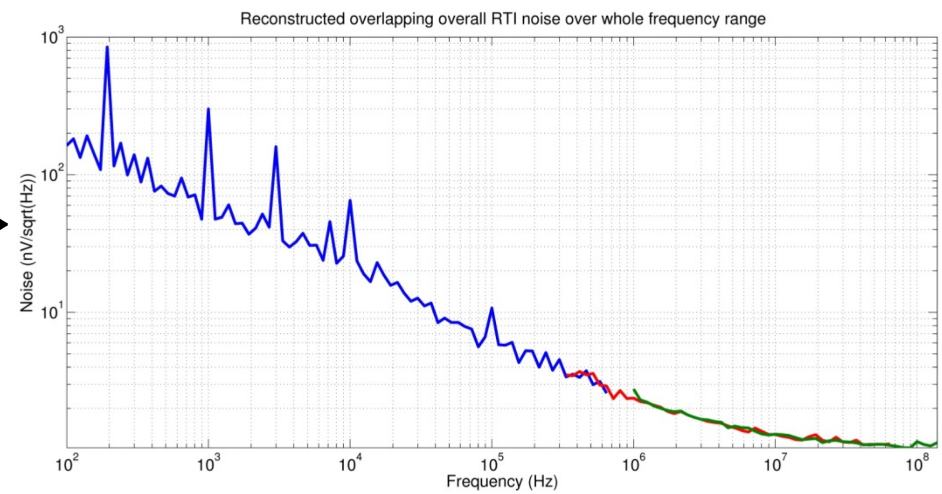
Noise characterization software



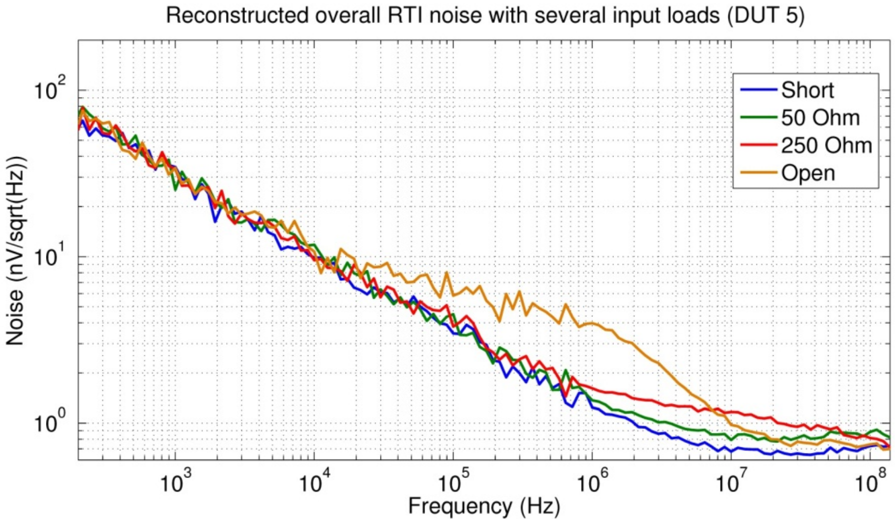
Principle of operation

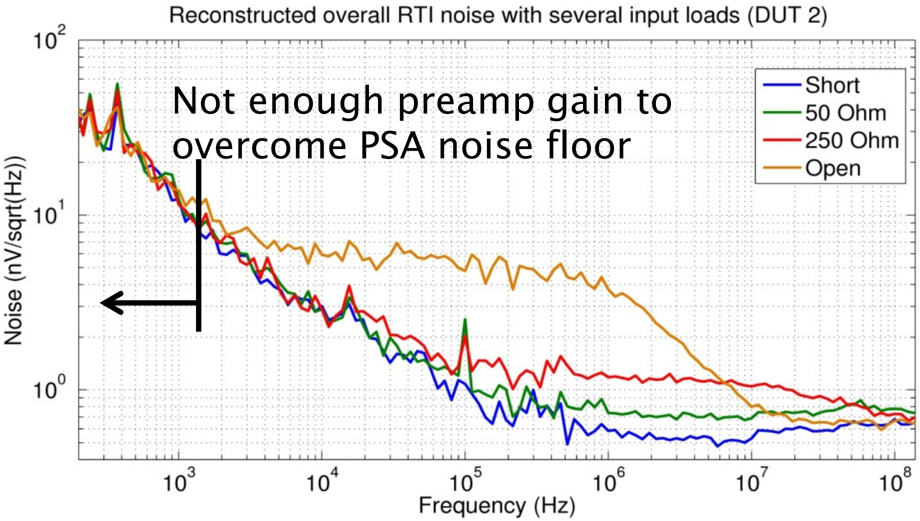
- Output noise measured through overlapping paths.
- Minimum measured level above instrument noise floor must be guaranteed.
- Output noise corrected by LNA gains to achieve referred to input (RTI) noise.

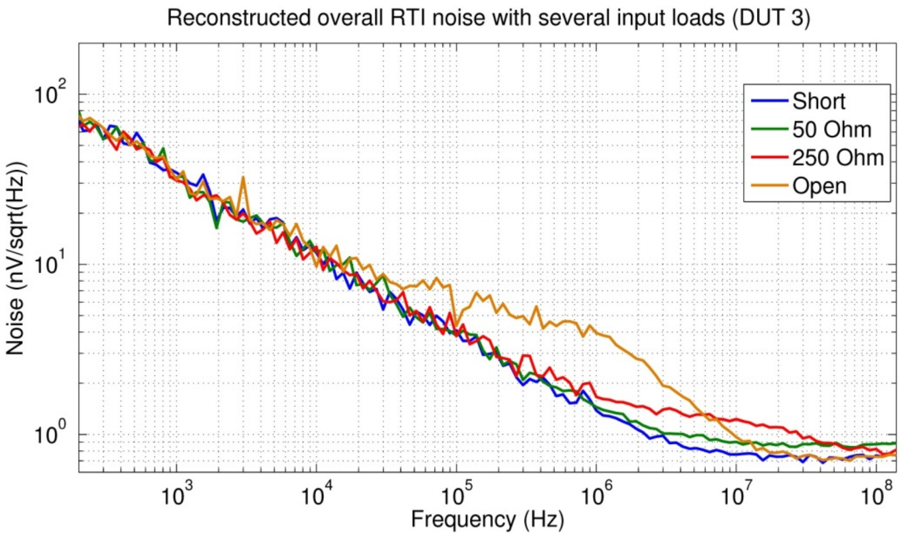


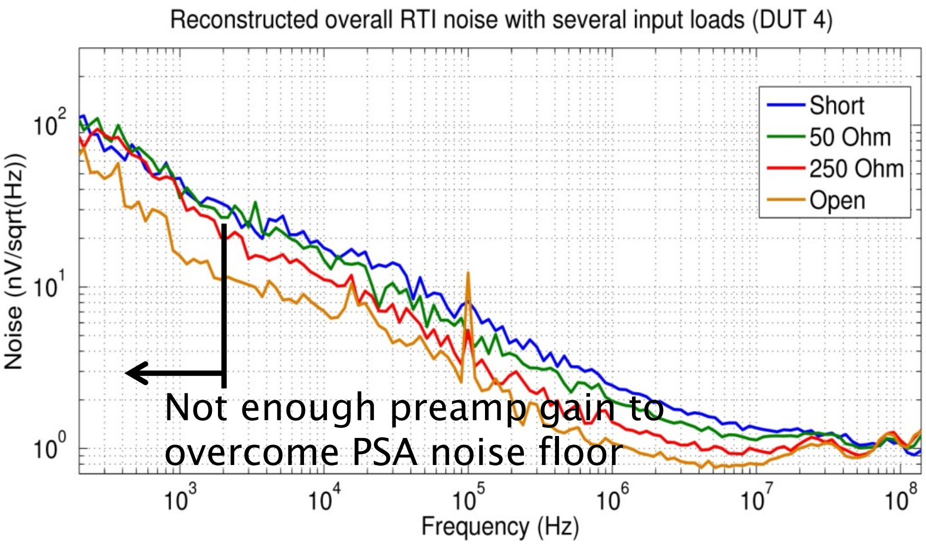


Noise plots (room temp.) from some DUTs



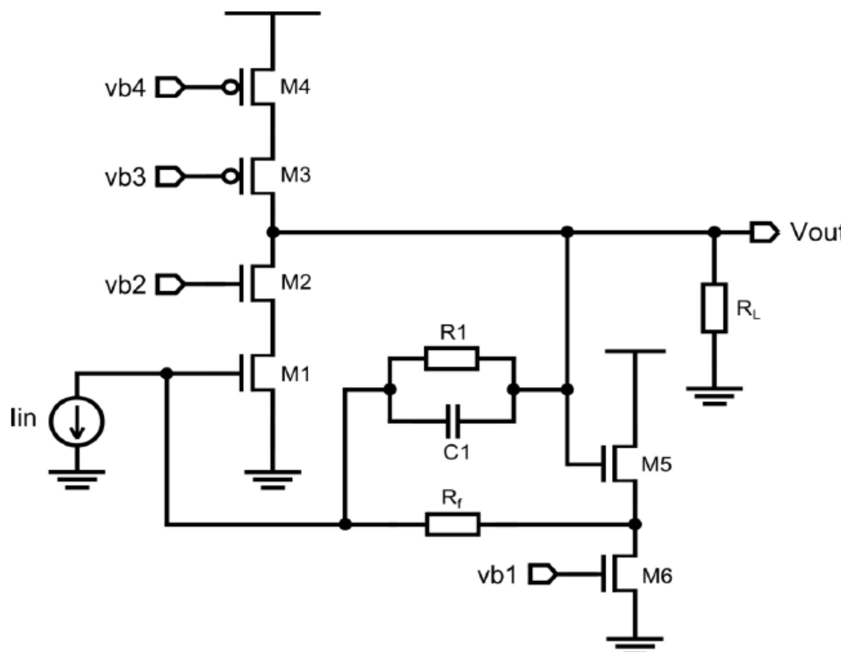






Challenges in the new HEC design

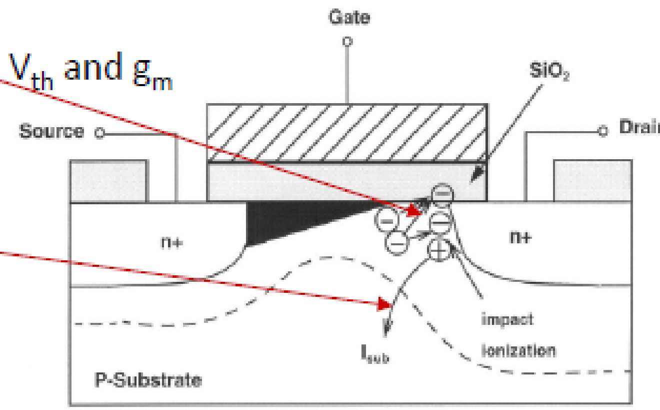
- The basic proposed structures are not complex:
  - Common topologies: cascodes + feedback
  - PMOS, NMOS (big transistors to lower noise)

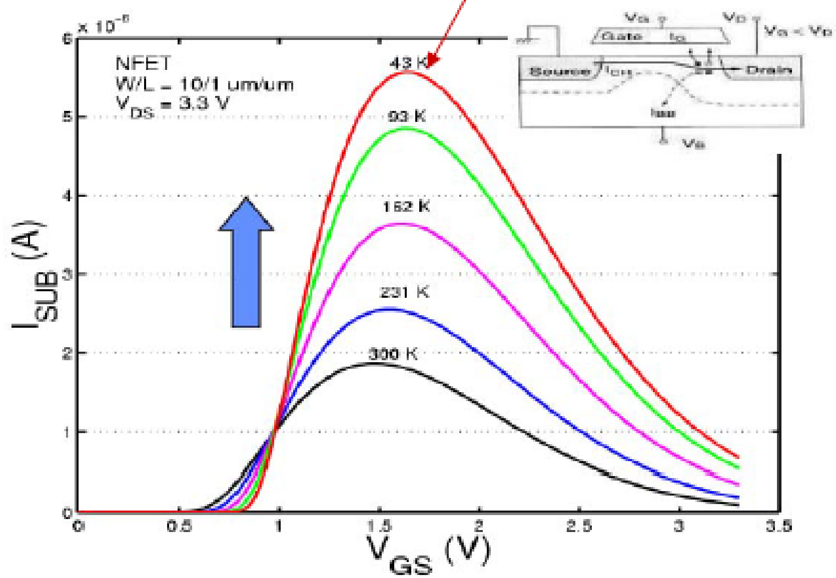


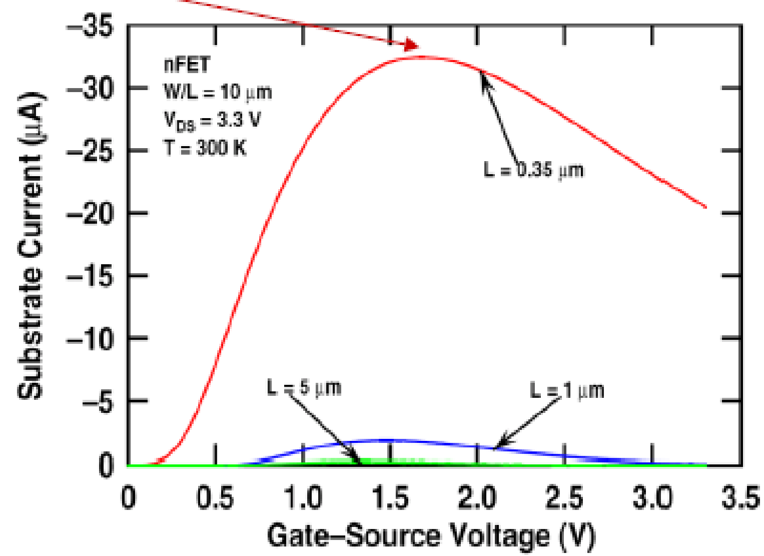
- The challenge:
  - The foundry (IHP) does not supply cryogenic or irradiation models for simulation
  - Characterization of devices under these conditions

CMOS reliability @ cryo temperatures

- ***Degradation*** is due to ***impact ionization***
  - charge trap in oxide, interface generation → shift in V_{th} and g_m
- ***Substrate current*** is a ***monitor of impact ionization***
  - increases with drain voltage
  - is higher in short channel devices
  - has a maximum at $V_{gs} \approx V_{ds}/2$
  - increases as the temperature decreases







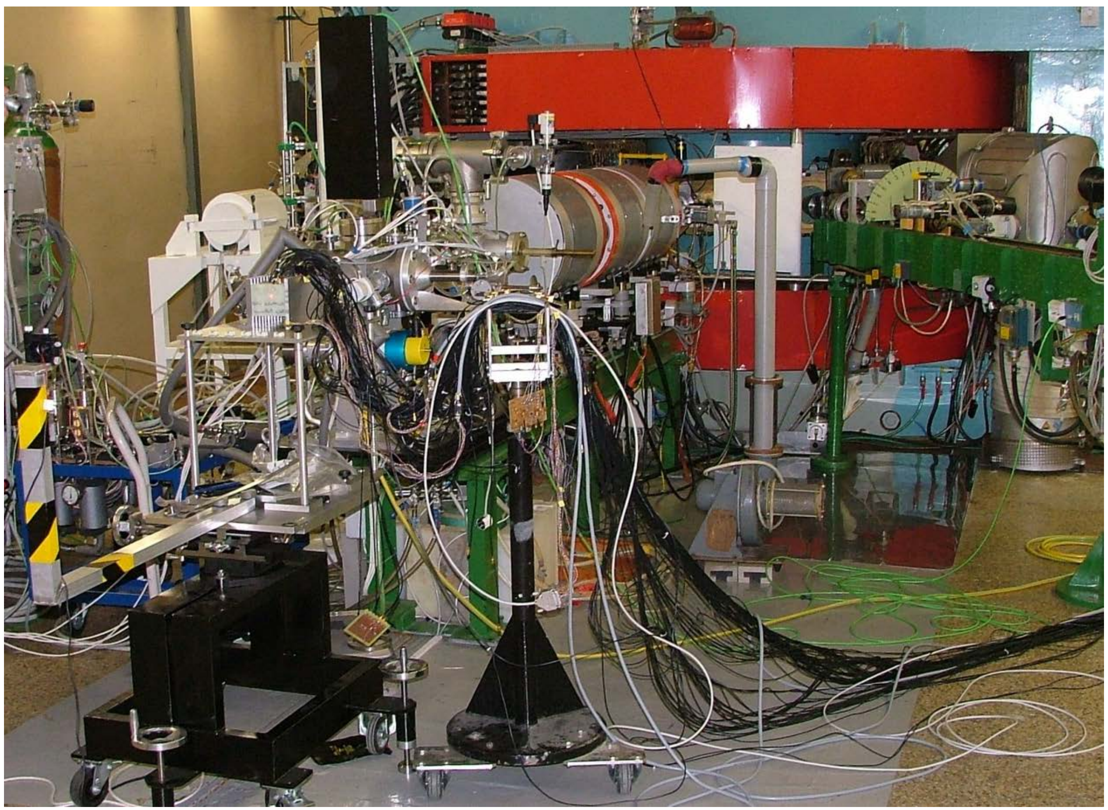
- Commercial technologies are rated 10 years lifetime (10% shift) in worst case continuous operation: T = 220 K, $L = L_{min}$, V_{ds} = nominal V_{dd}, $V_{gs} \approx V_{ds}/2$)

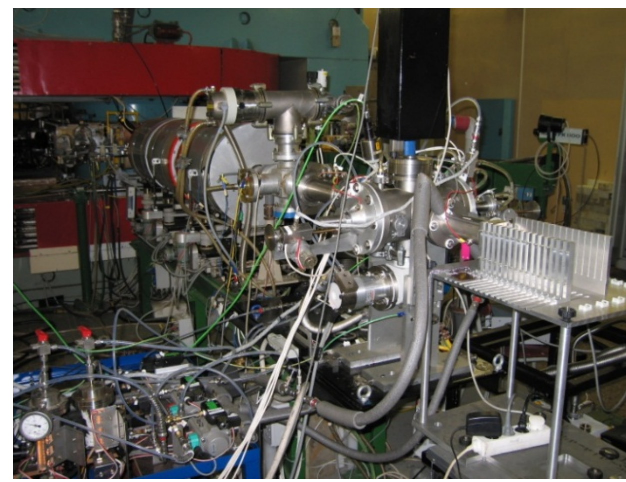
CMOS reliability @ high irradiation levels

- Gamma-ray photons:
  - Electron-hole pairs
  - Photoelectric effect, Compton effect
  - Ionization and displacement damage
- Neutrons:
  - Elastic scattering
  - Ionization and displacement damage
- Protons:
  - Electron-hole pairs
- Oxide insulating layer (SiO_2) degradated, MOS parameters affected:
  - **Threshold voltage** (shift)
  - Transconductance
  - Leaking current
  - Noise
  - Mobility

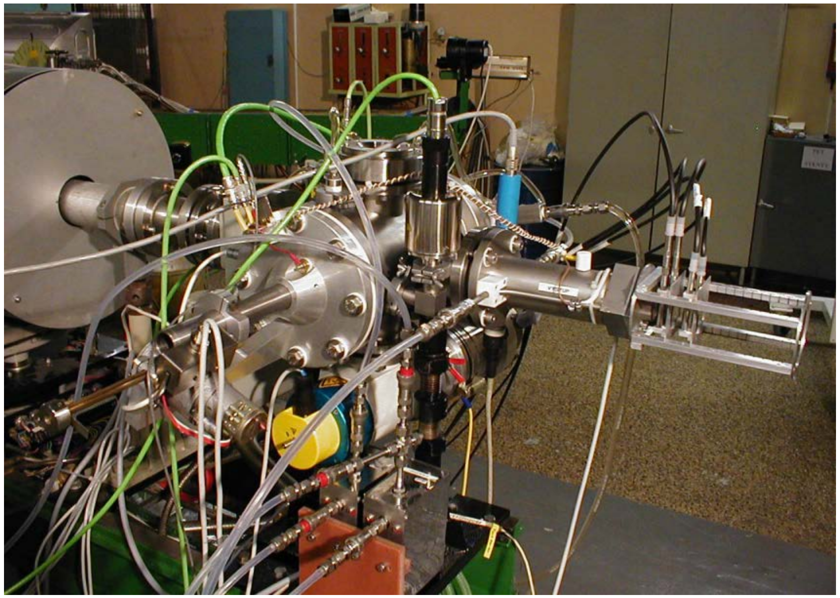
Irradiation tests

- Fast Neutron Facility at Nuclear Physics Institute (NPI) in Rez near Prague

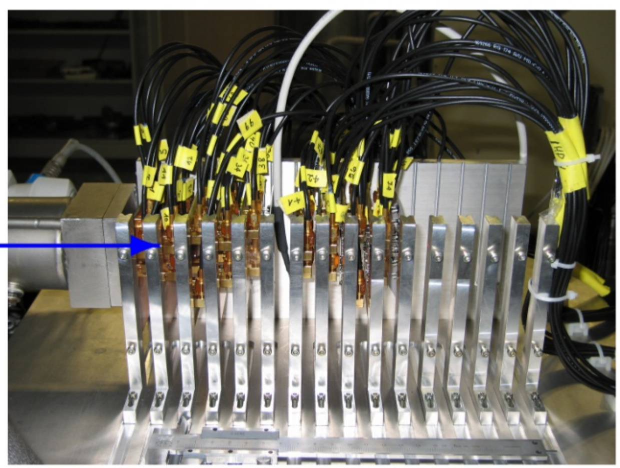




Neutron irradiation test at NPI (Dec. 2012)

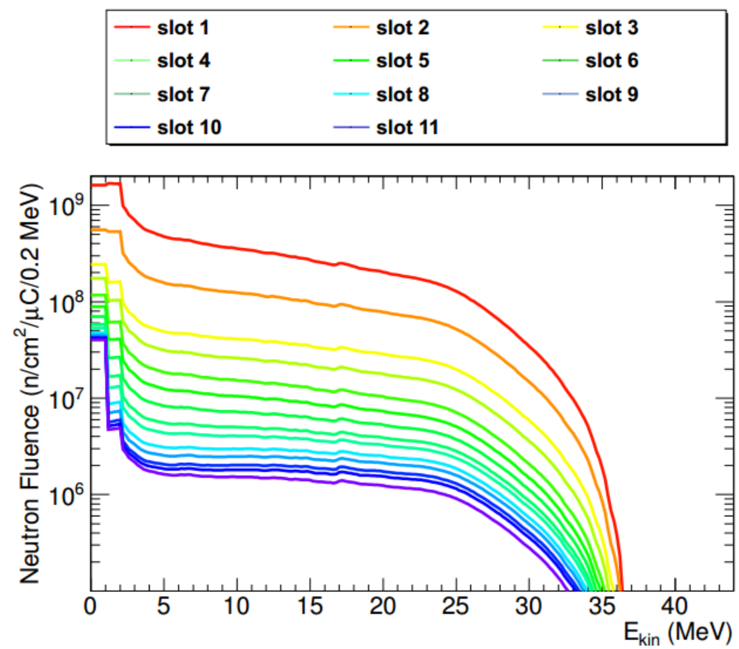


Neutron beam



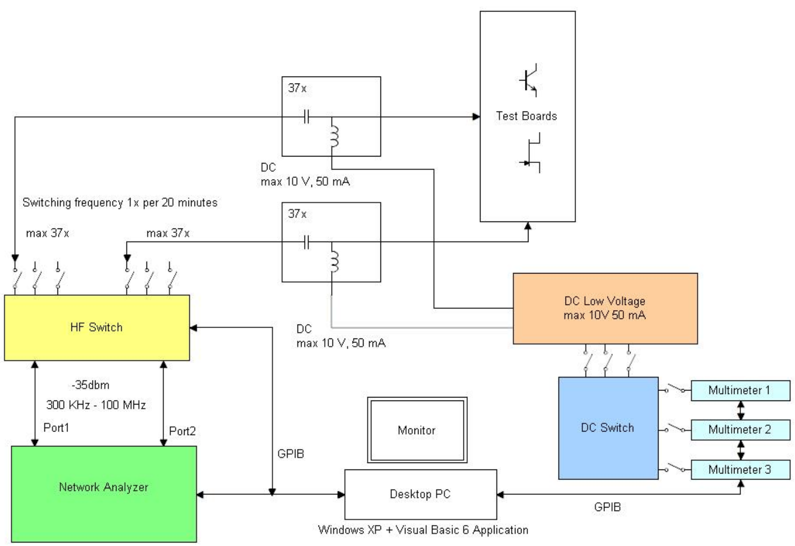
Aluminum frame with boards

- 37 MeV proton beam from NPI Cyclotron U-120M
- 15 uA maximum beam intensity
- Heavy water target, fast neutrons from D2O(p, xn) reaction
- Neutron flux up to 10^{11} n/cm^2/s with approx. 15 MeV mean energy
- Maximum neutron energy of approx. 36 MeV

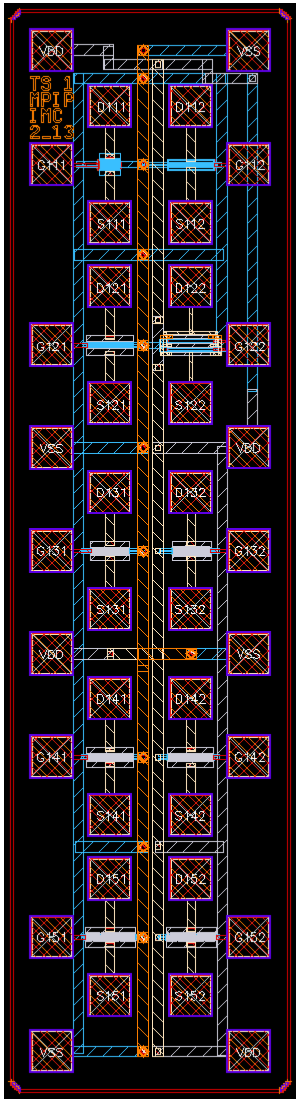


Mobile setup for radiation tests

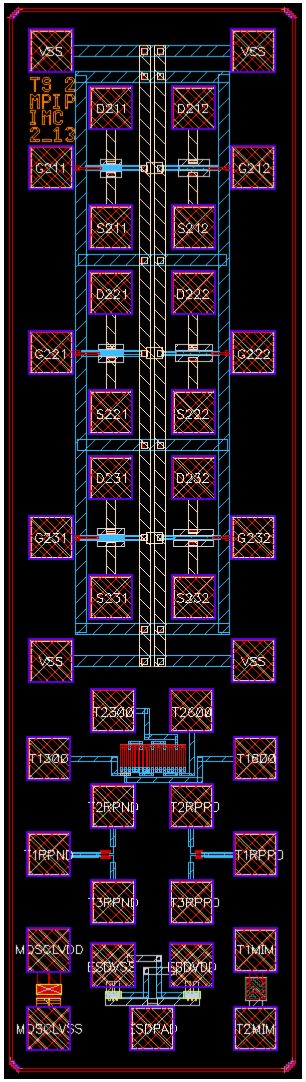
- 62 channels (31 devices)
  - Network Analyzer
  - Source meters
  - Programmable RF switch matrixes
  - Software
- Measurements over 40 m cables!
- DC and s-parameter measurement
- Tests @ room temp. and cryogenic (lab)



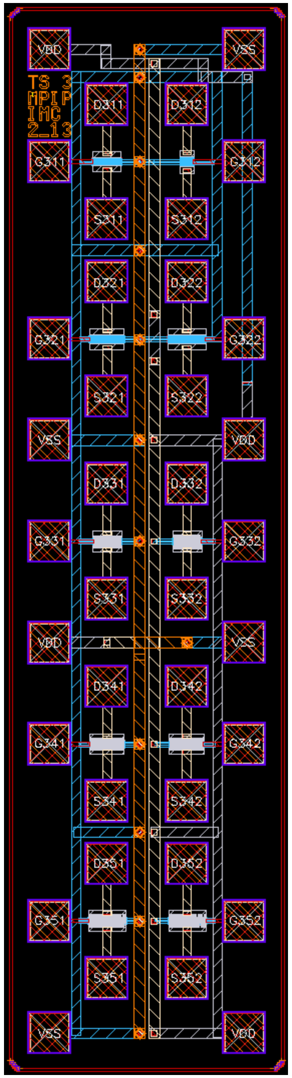
Samples designed at the MPI (Virtuoso, Cadence)



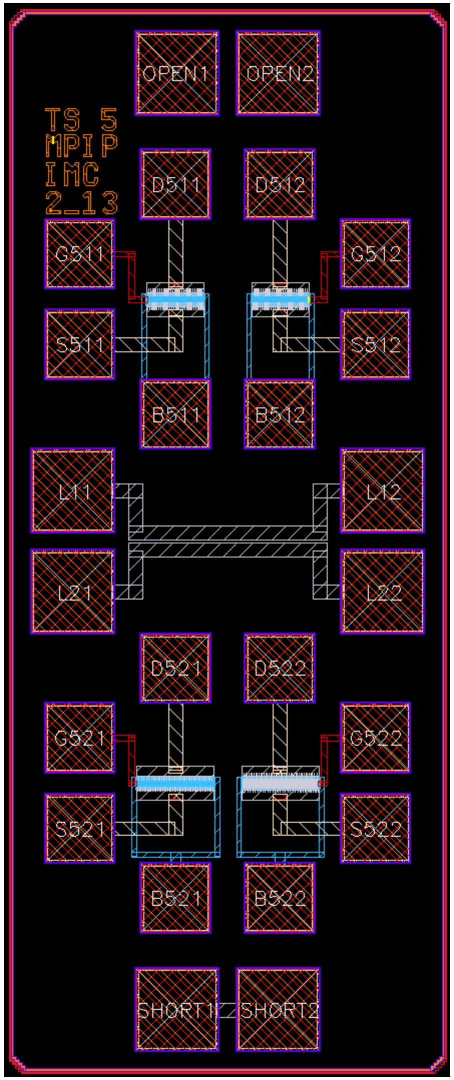
TS_1



TS_2

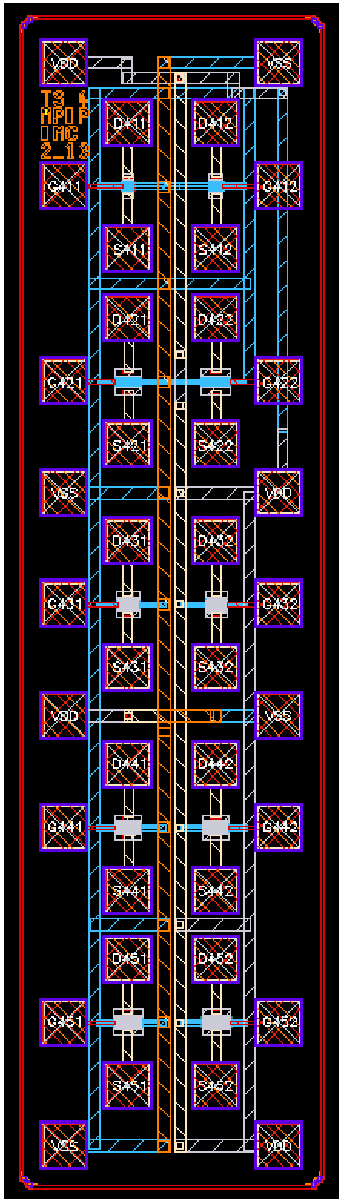


TS_3

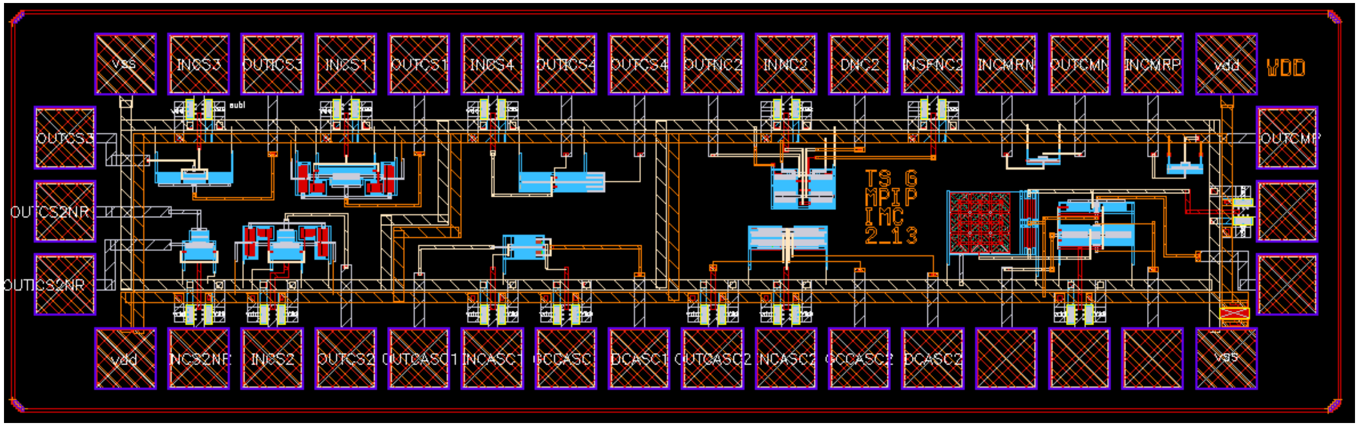


TS_5

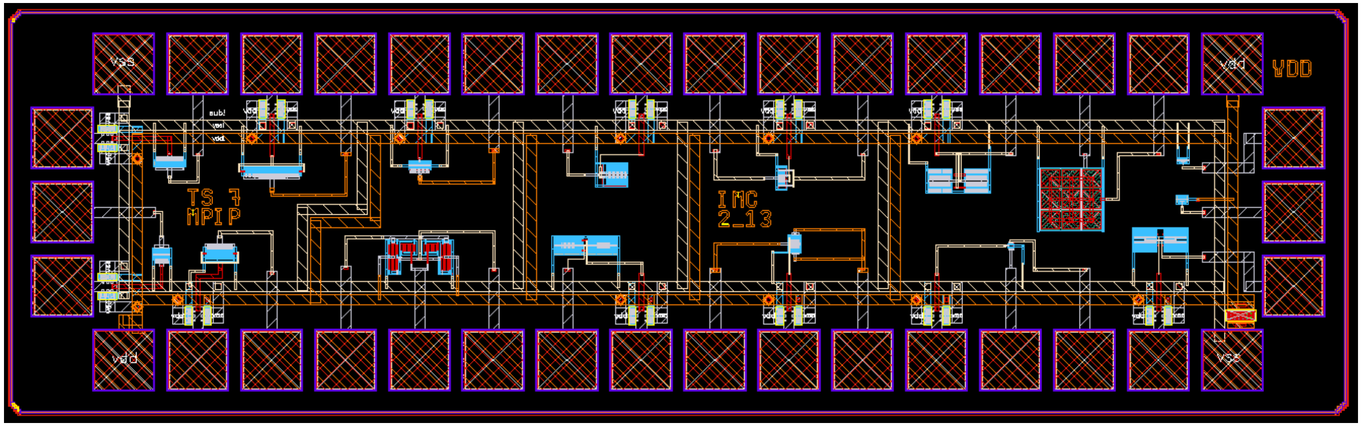
Samples designed at the MPI (Virtuoso, Cadence)



TS_4

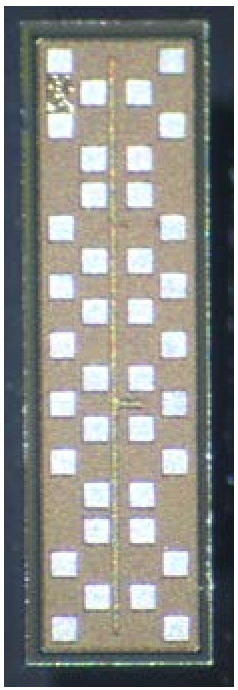


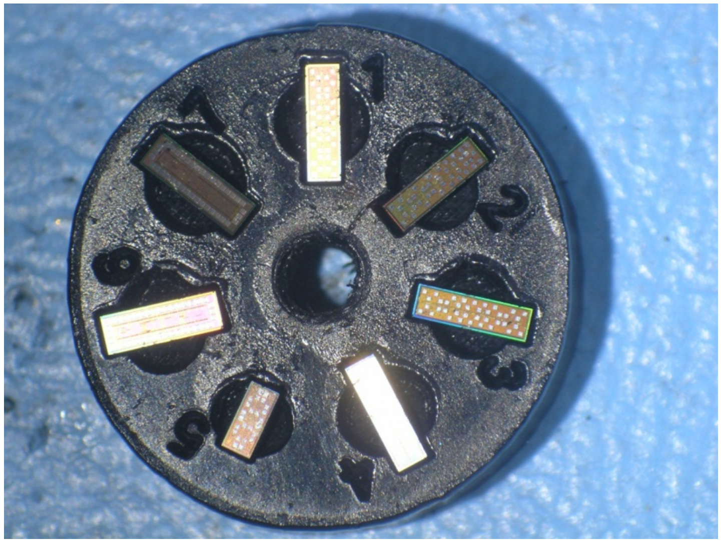
TS_6

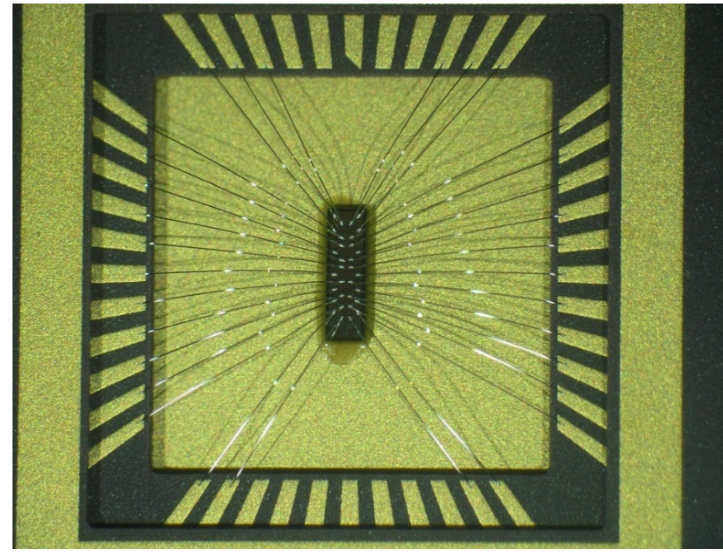


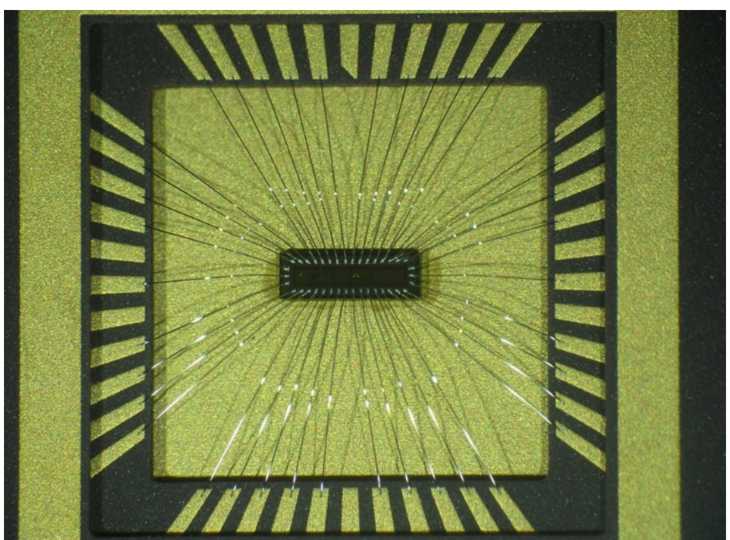
TS_7

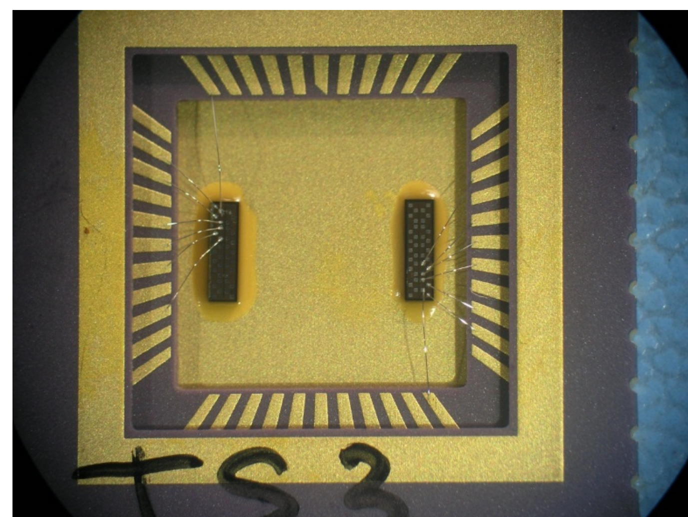
Packaging / bonding of samples designed for tests





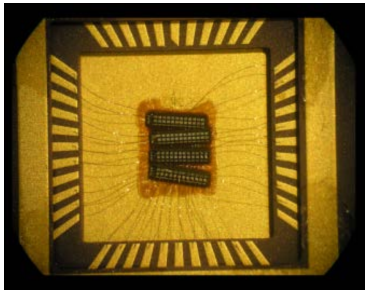


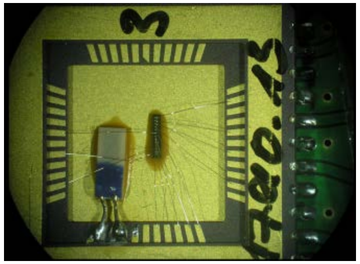


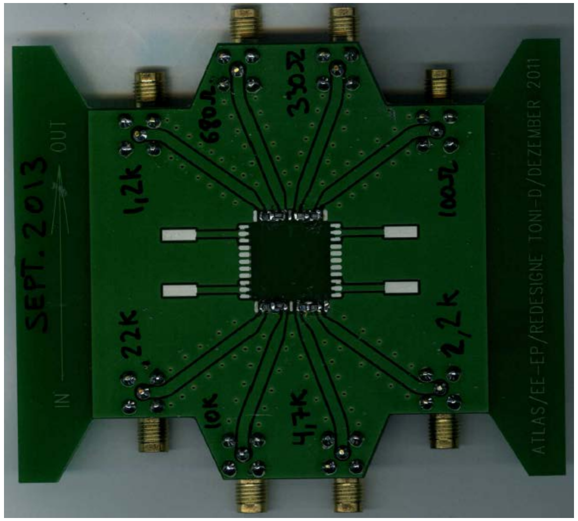


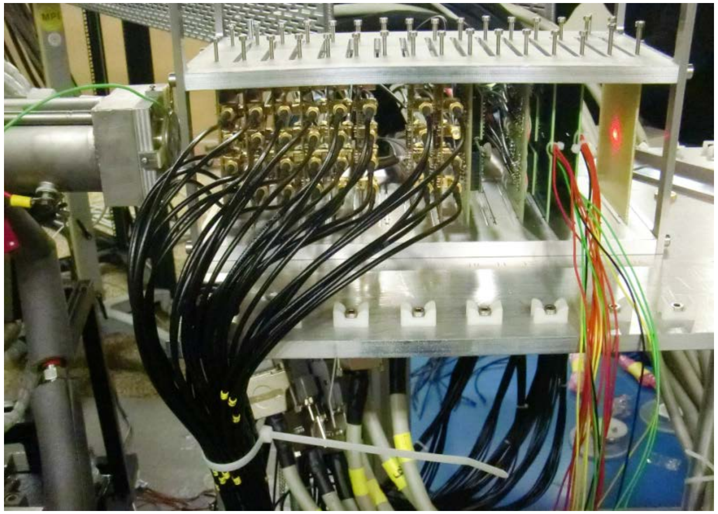
Packaging of samples and tests

- Relevant transistor parameters:
  - DC parameters: Vth, gm, ro
  - Frequency behavior (Scattering parameters)
- Used for cryogenic measurements and irradiation tests









Preliminary results after irradiation tests

Linear Extrapolation Method

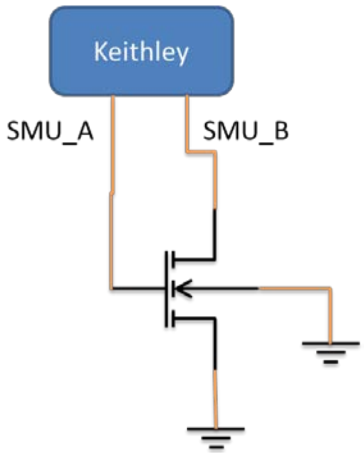
Transistor (V_{th} V)	No Irradiated	S4RA(1.9)	S4RC(3.1)	S4RB(3.6)	S1RA(11.7)	S1RC(19)	S1RB(22.1)
T111	0.601	0.572	0.584	0.586	0.566	0.569	0.584
T121	0.619	0.605	0.605	0.609	0.633	0.606	0.61
T221	0.624	0.624	0.626	0.623	0.627	0.632	0.624
T231	0.62	0.619	0.619	0.617	0.623	0.627	0.619
T511	0.604	0.605	0.612	0.611	0.598	0.595	
T522	0.592	0.59	0.599	0.596	0.586	0.59	0.587

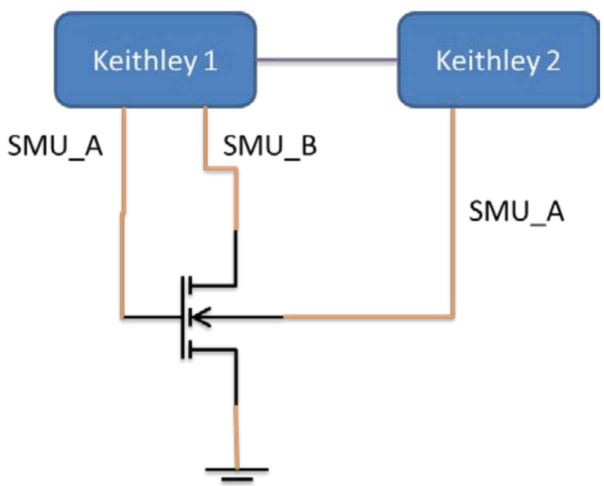
All Values are inside the foundry target. No significant shift observed

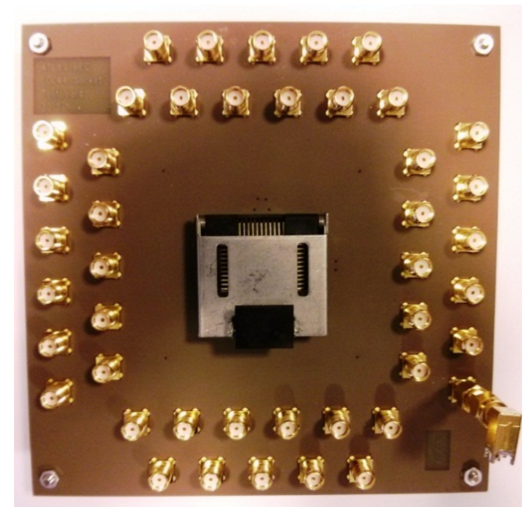
IHP Target	min	max
V_{th}(V) (V_{bulk}=0V)	0.56	0.67

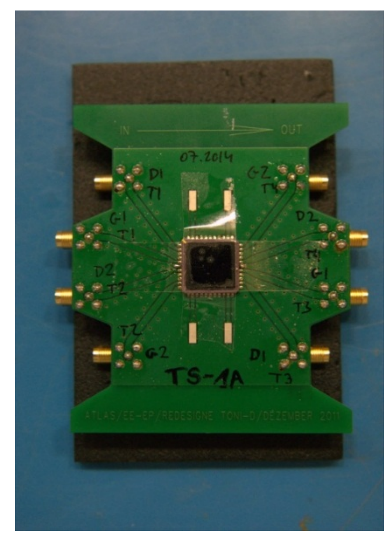
Cryogenic measurements

- The SMU model 2636B (Keithley) was used for the DC measurements.





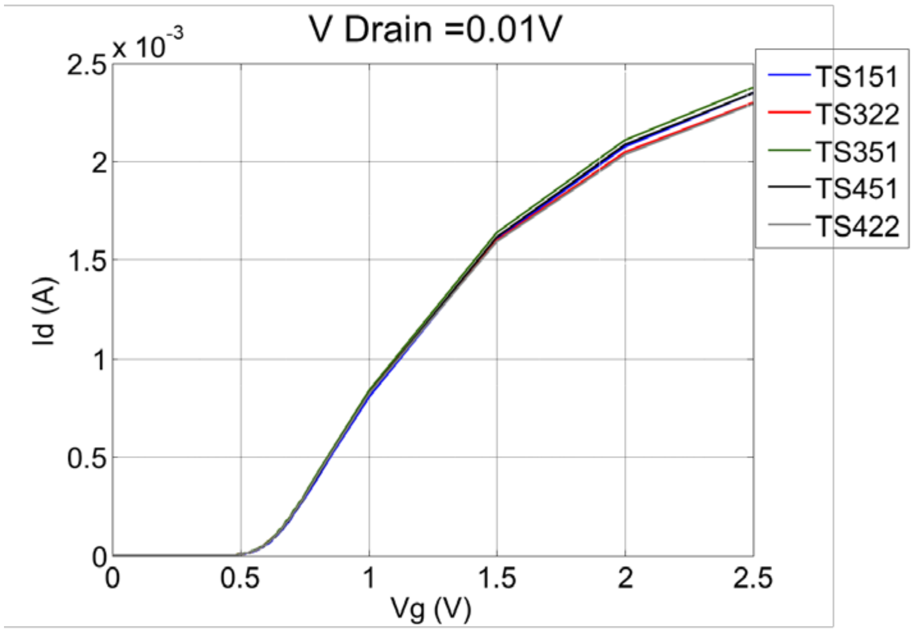


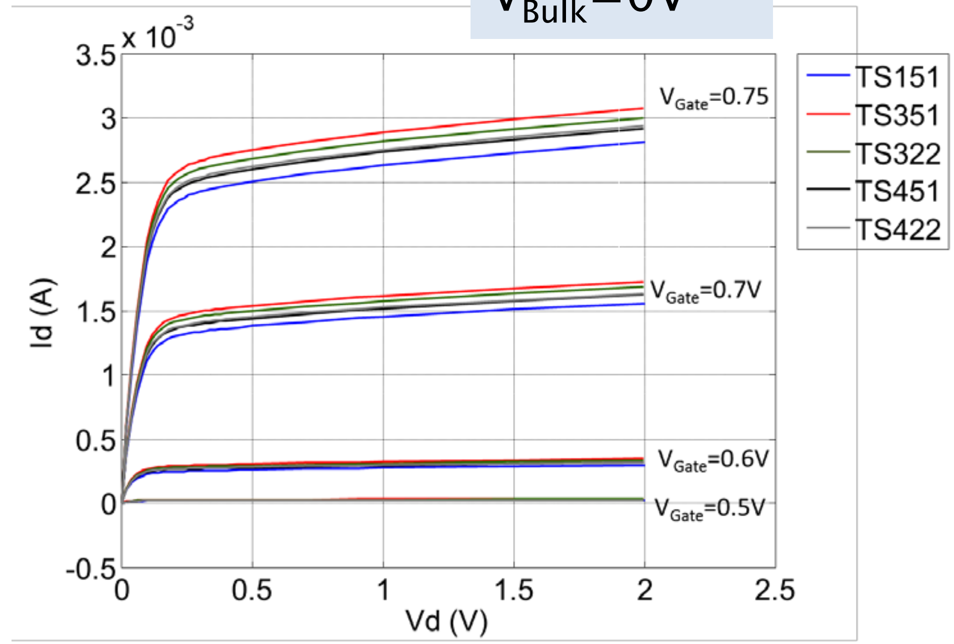


T151 has 80 fingers
T322 T351 have 60 fingers
T451 T422 have 40 fingers

Room temperature

W=750um
L=600nm
V_{Bulk}=0V





Linear Extrapolation Method

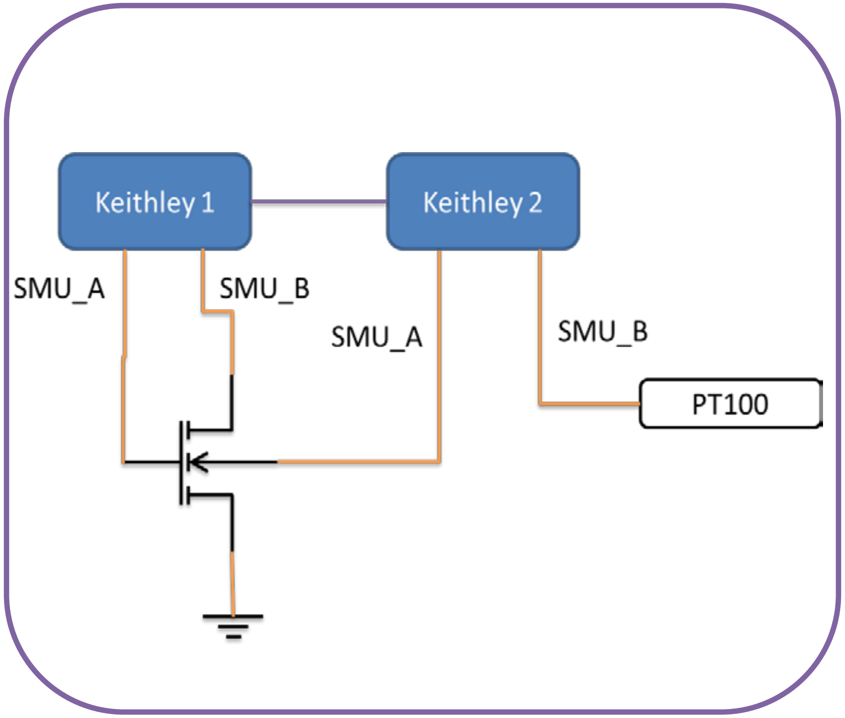
Type	T151	T351	T322	T451	T422
V_{th}(V) (V_{bulk}=0V)	0.607	0.599	0.6	0.61	0.607
V_{th}(V) (V_{bulk}=-0.5V)	0.742	0.734	0.736	0.73	0.729

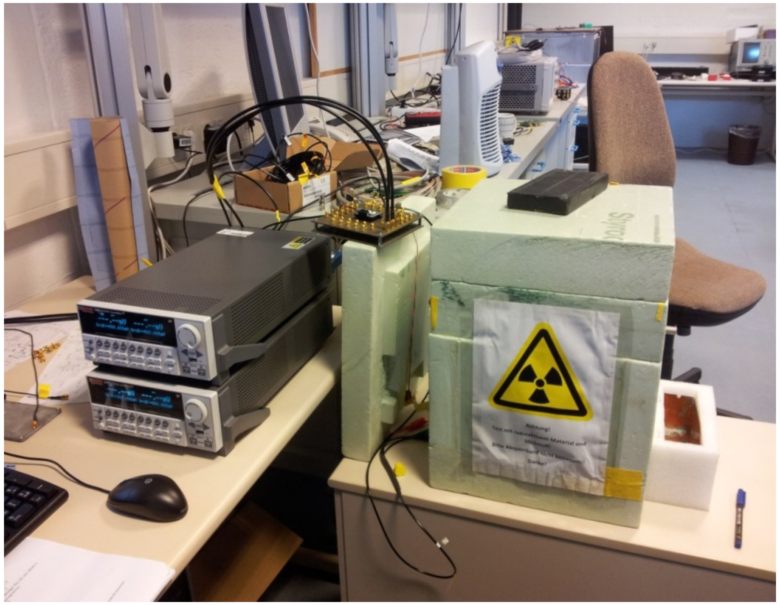
Type	mean	std
V_{th}(V) (V_{bulk}=0V)	0.606	4.83e-3
V_{th}(V) (V_{bulk}=-0.5V)	0.734	5.21e-3

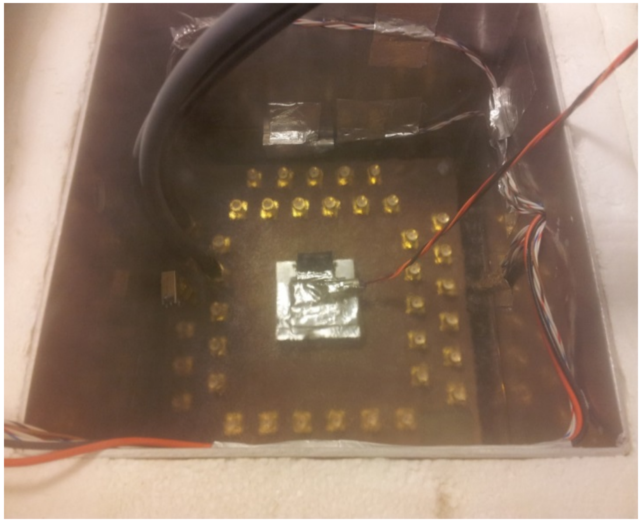
IHP Target	min	max
V_{th}(V) (V_{bulk}=0V)	0.56	0.67

Cold Setup

Schematic





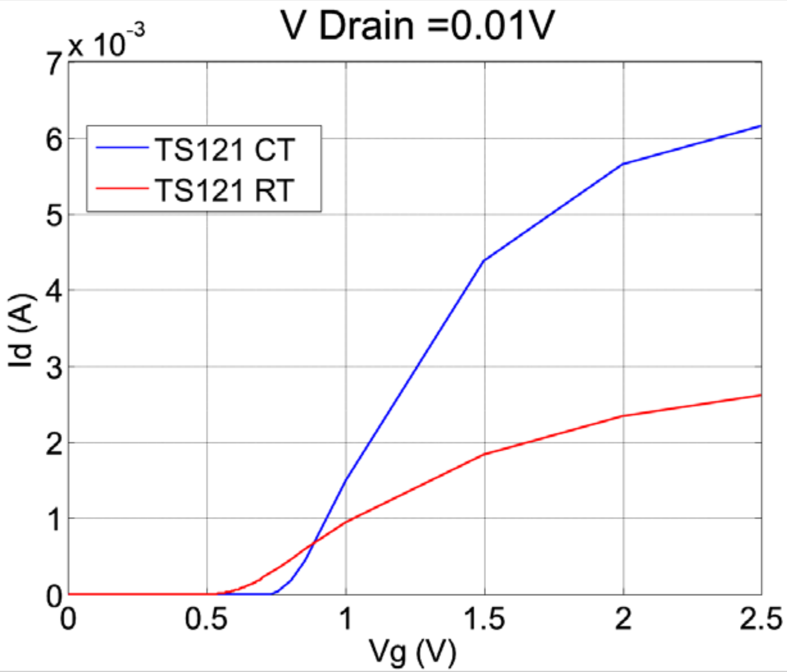


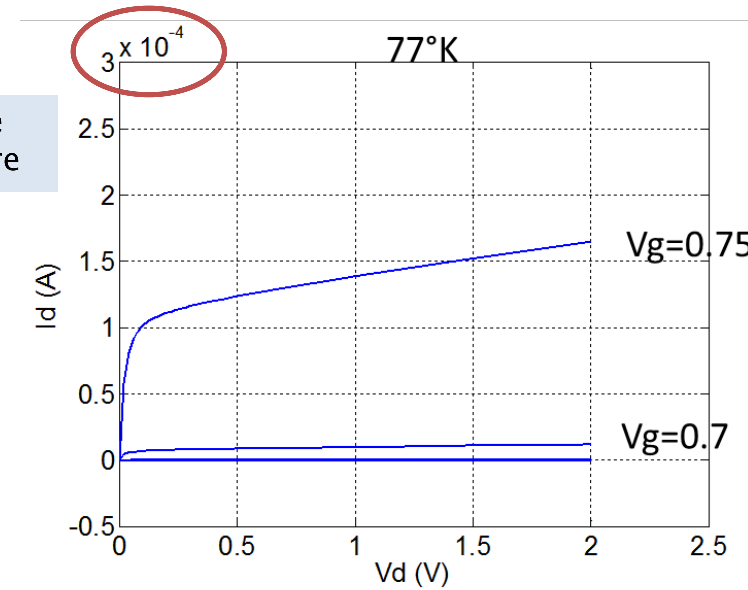
- Curves $I_{Drain} - V_{Gate}$
- Curves $I_{Drain} - V_{Drain}$

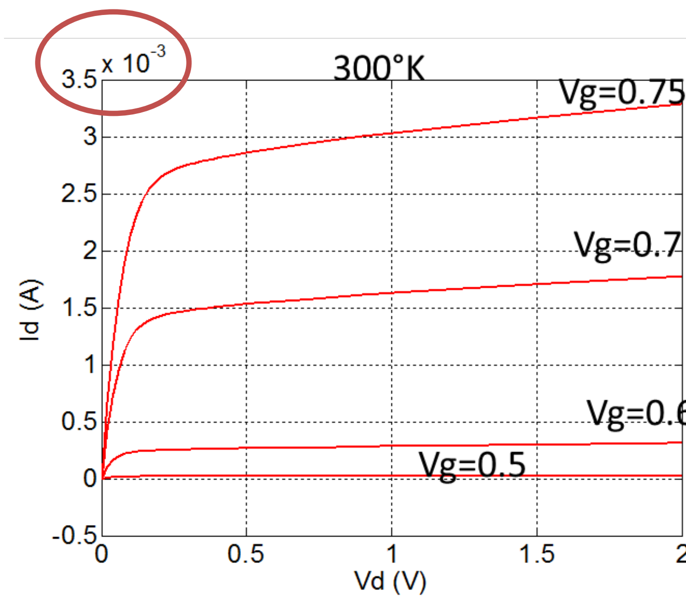
Transistor performance @ 77K

T121:
- W=750um, L=480nm
- 80 fingers

CT: Cold Temperature
RT: Room Temperature







	T121 CT (77°K)	T121 RT (300°K)
V_{th}(V)	0.796	0.619

EKV model for simulation

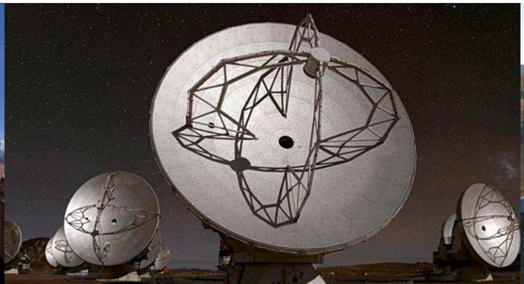
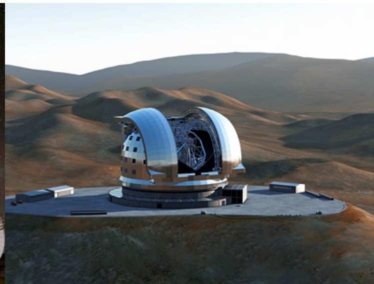
- EKV: C. C. **E**nz, F. **K**rummenacher, y E. A. **V**ittoz (1995)
- Accepted by many simulators (Cadence)
- SGV25V parametric transistor model development:
  - @ room temperature and cryogenic
  - Able to model irradiation effects
  - EKV 2.6
- Some parameters already extracted from tests:
  - VTO, UO, NSUB

ESO: history and mission

- 1962
  - The European Southern Observatory (ESO) was created by five Member States with the goal to build a large telescope in the southern hemisphere
  - This became the 3,6 m telescope on La Silla (1976)
- 2015
  - 14+2 Member States (~30% of the world's astronomers)
  - Paranal is the world-leading ground-based observatory
  - ALMA (in partnership) has started observations and construction is completed
  - Approval of 39,3 m E-ELT on Armazones
- Mission
  - Develop and operate world-class observing facilities for astronomical research
  - Organize collaborations in astronomy

www.eso.org



ESO Member States

1962 Belgium, France, Germany, The Netherlands, Sweden

1967 Denmark

1982 Switzerland, Italy

2001 Portugal

2002 United Kingdom

2004 Finland

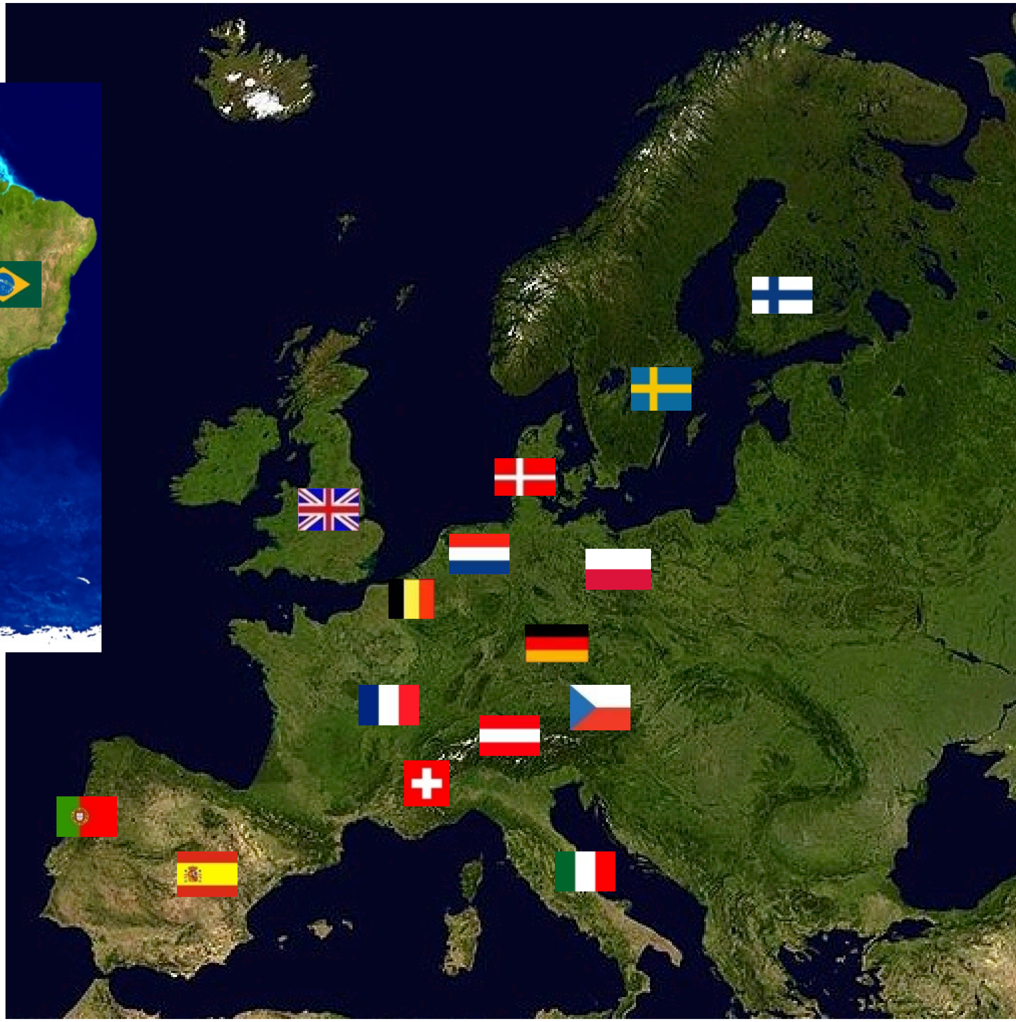
2006 Spain

2007 Czech Republic

2008 Austria

2010 Brazil (ratification pending)

2014 Poland (ratification in process)



Will increase further:

- Germany hosts HQ near Munich
- Chile hosts the Observatories but is not a Member State

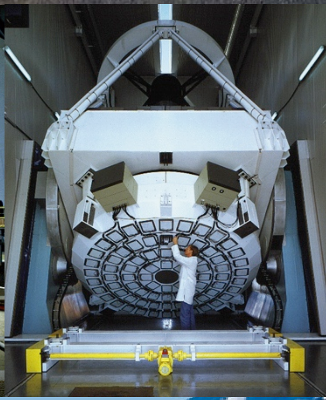
ESO’s Sites


Garching bei München
Chajnantor
Paranal
La Silla
Santiago
Earth at Night
More information available at:
http://antwrp.gsfc.nasa.gov/apod/ap001127.html
Astronomy Picture of the Day
2000 November 27
http://antwrp.gsfc.nasa.gov/apod/astropix.html

ESO multiple programmes

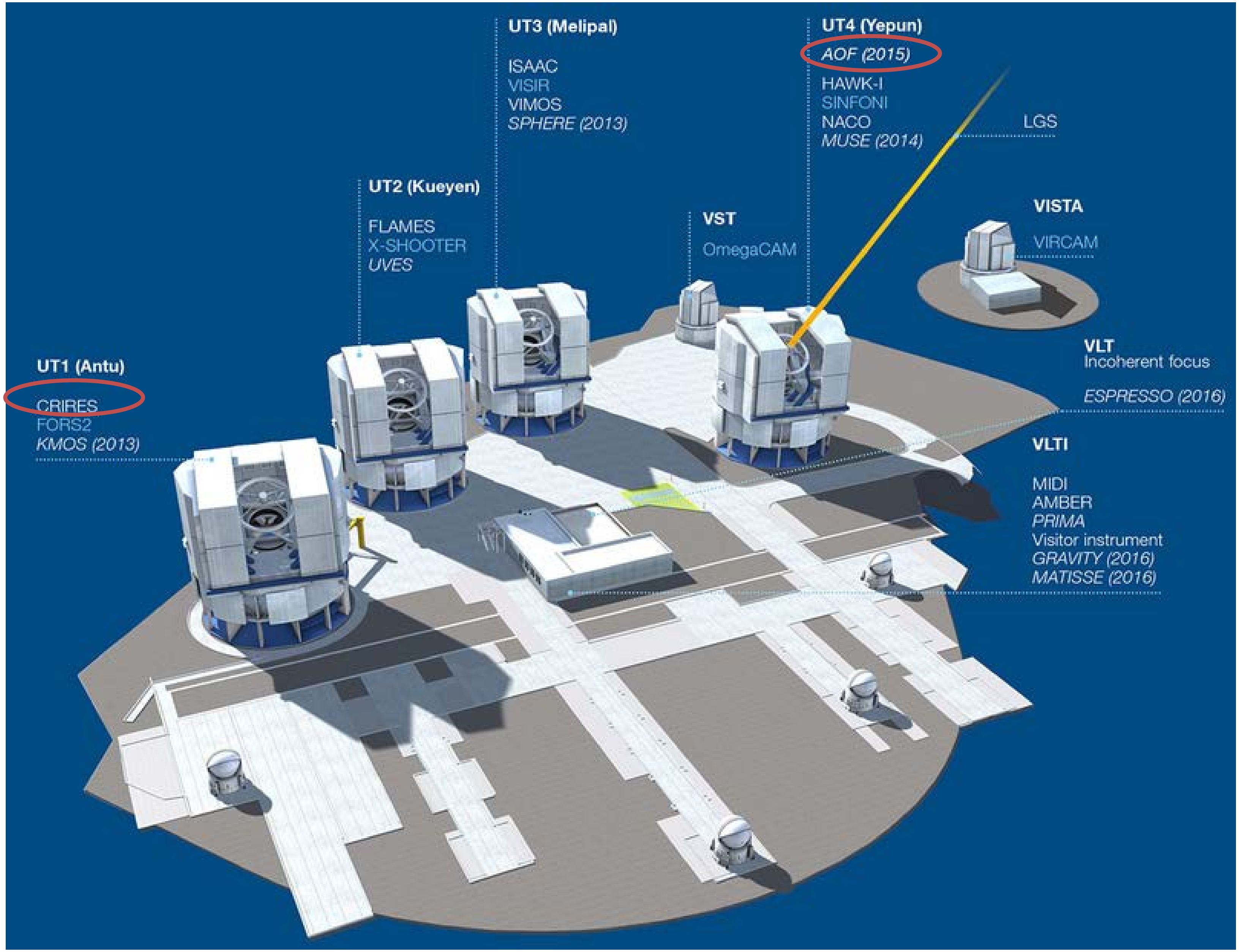
- Visual/infrared light
  - La Silla telescopes
  - VLT, VLTI, VISTA and VST on Paranal
  - E-ELT to come, on Armazones
- Submillimeter radio waves
  - APEX
  - ALMA
  - In partnerships (at Chajnantor)



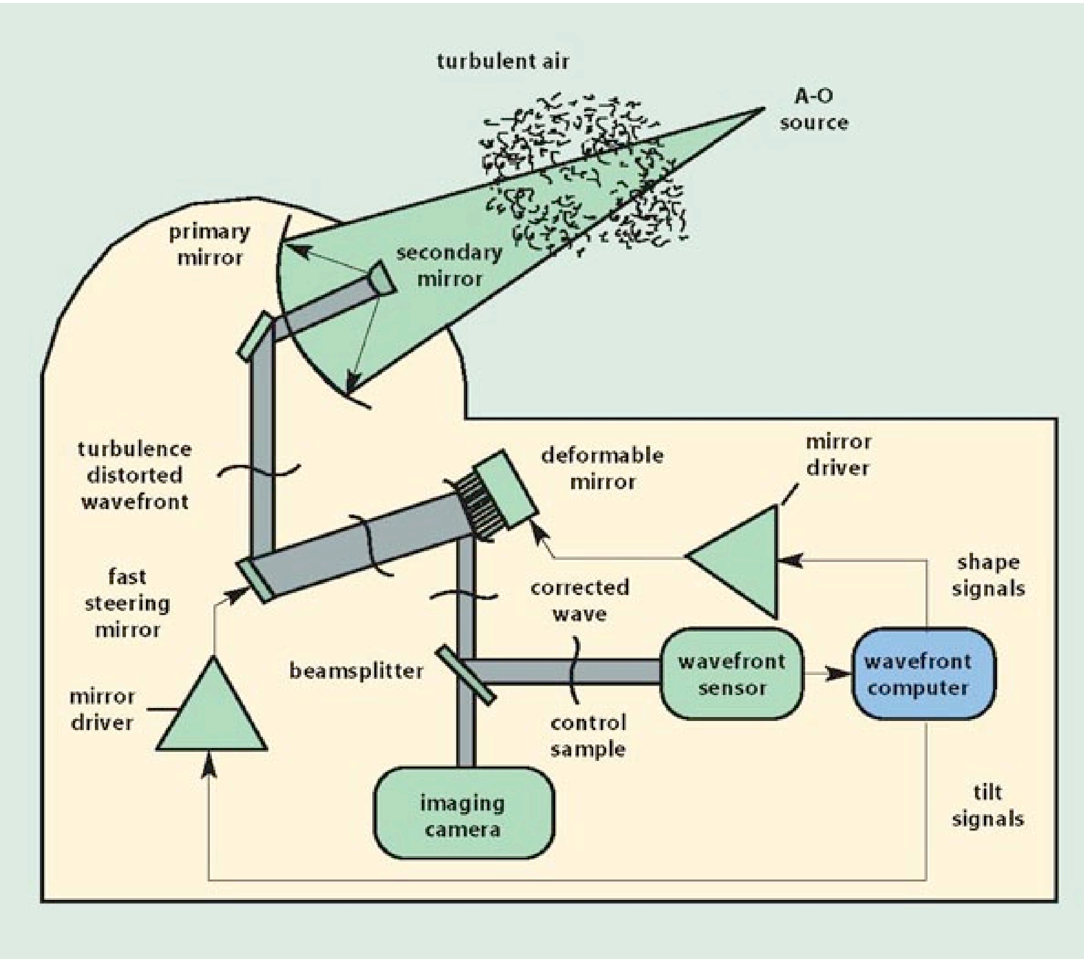



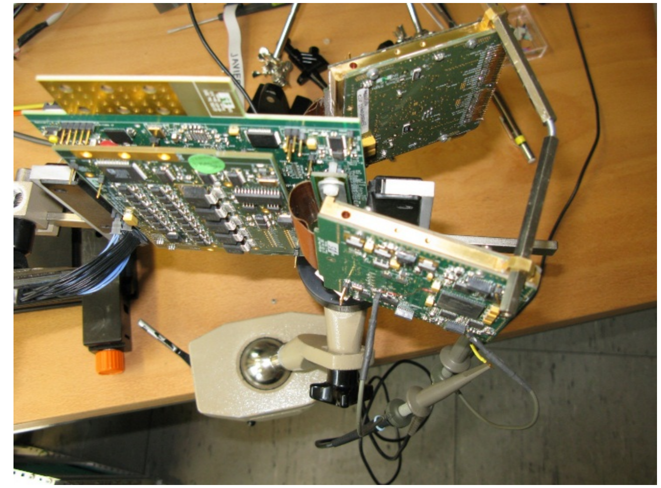

The Very Large Telescope

VLT instruments

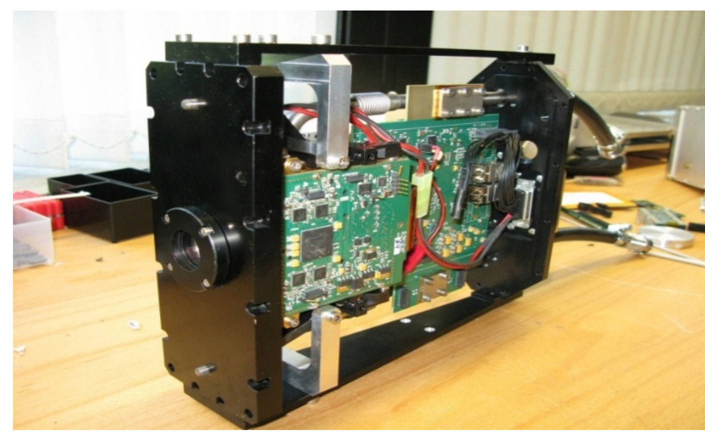


Adaptive optics facility (AOF)

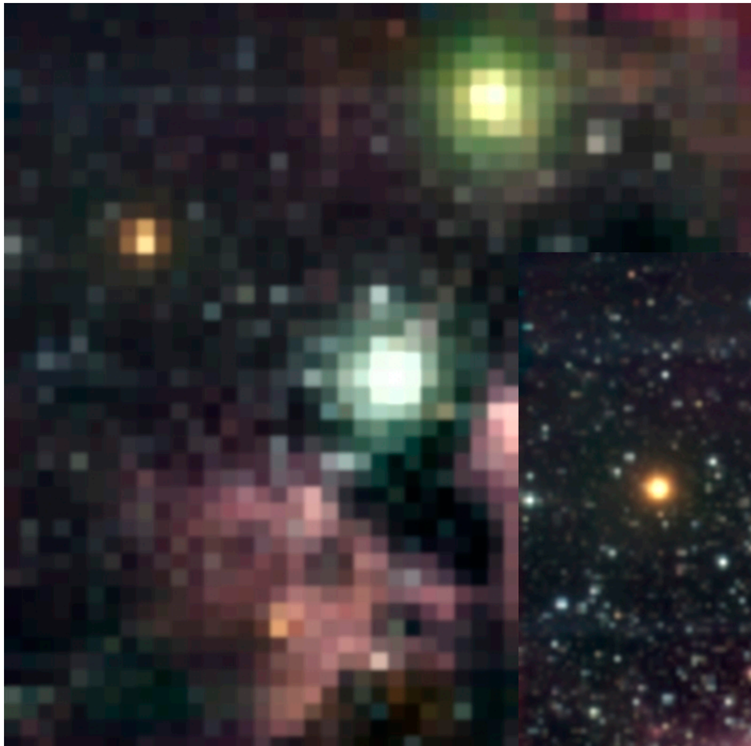




VLT AOF WFS (wave front sensor)
Assembled prototype in 2011

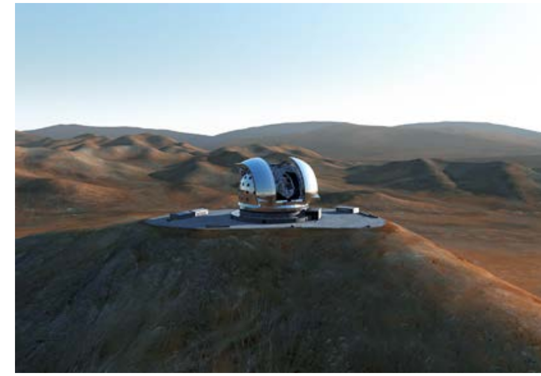


Spectacular Resolution



HST (Hubble Space Telescope)

VLT+AO



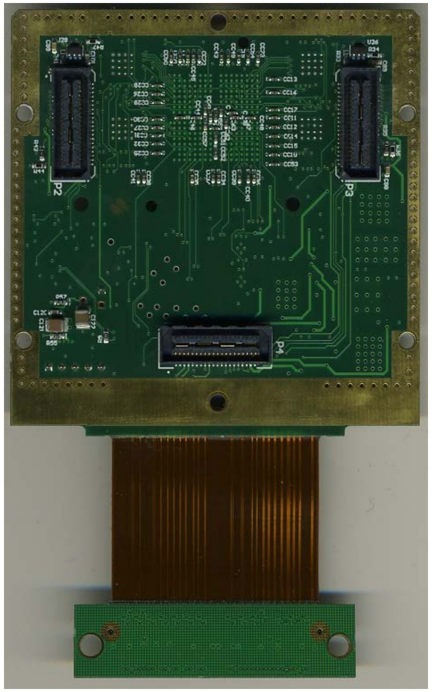
E-ELT

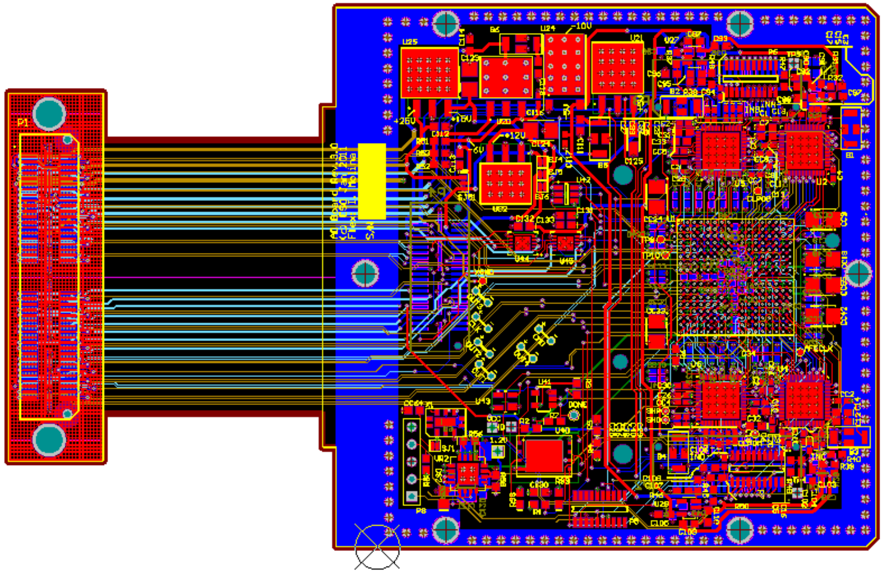
AOWFS

- Fast reading of up to 10 Mlines per second.
- 8 output ports, 14-bit ADCs.
- Frame rate of up to **12oo fps**
- High-voltage, high-speed clock driver generation.
- High-speed video sampling, read **noise** < 0.1e-
- Prototipe:
  - **6 boards**: Bias, 2xClock, Main, 2xAD.
  - Cooling block (CCD220), cooling pipes, housing.
  - House keeping and power external connectors.
  - Fiber optics signal interfaces.

New AD board design

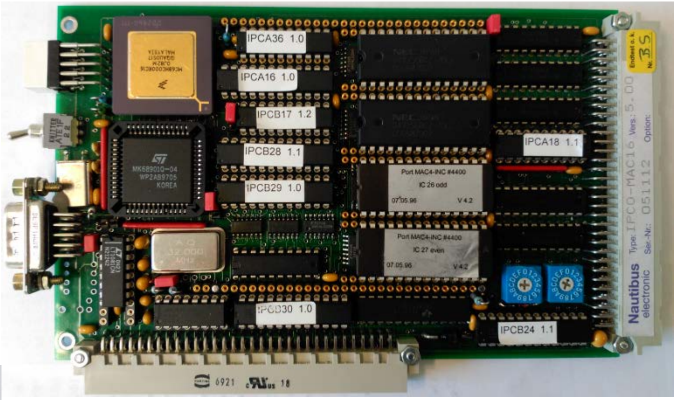
- Xilinx Spartan 6 LX16-25 FP(G)256:
  - Size constrained by location of ADCs (top and bottom).
  - Resources: up to 1 Gbps transceiver throughput, PLLs, DCMs, and logic resources.
  - Xilinx ISE Design Suite: main VHDL development tool.
  - Many new features embedded.
- Layout: Altium Designer ver. 9.4.0.20159

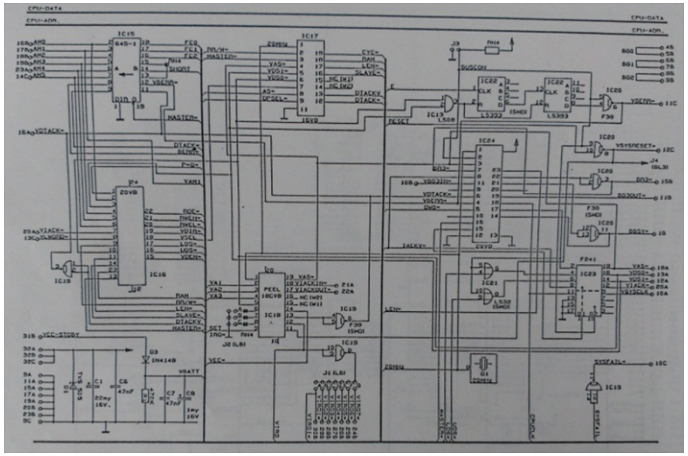




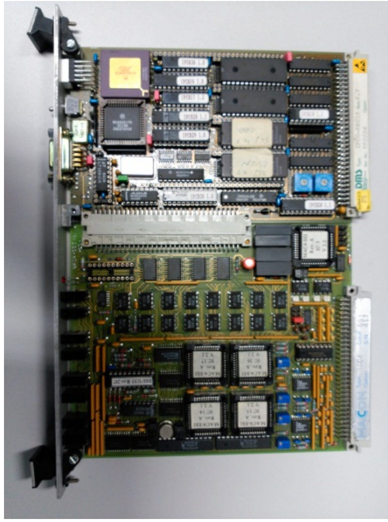
Motor controller board: obsolescence

- VME module
- Installed on many instruments (more than 100 boards)
- No further support from manufacturer
- Many old PLDs
- CPU: Motorola MC68000
- Peripheral Controller: MC68901
- Discrete RAM, ROM ICs
- Schematics in hard print





Real schematic sheet sample



Motor controller on FPGA: feasibility test

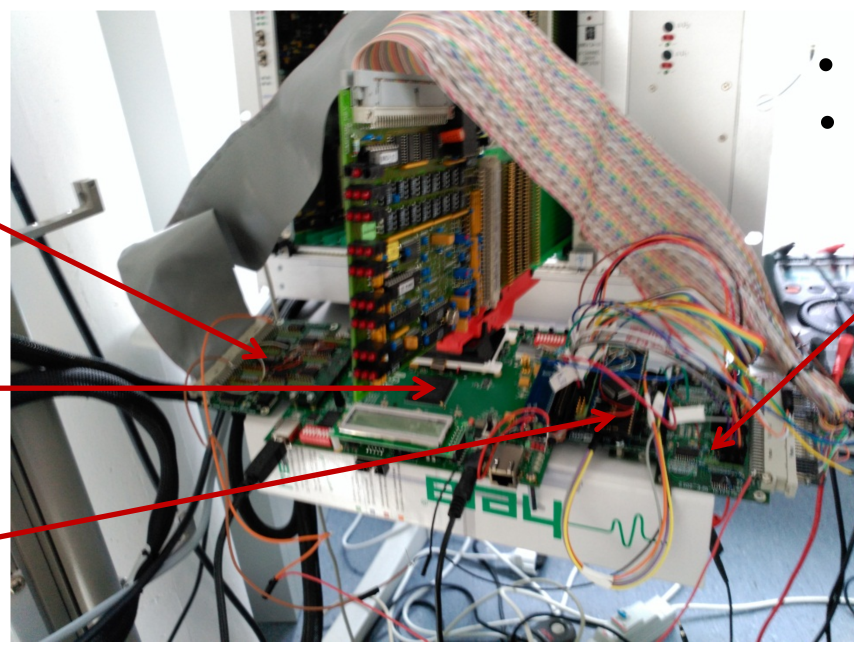
- Soft cores for uP and peripheral controller:
  - Open (SUSKA project: http://www.experiment-s.de/en)
  - IP cores: i.e., Millogic

- MC68SEC000 still in production (Freescale)
- VME bus buffers (interface, level translators)
- PLDs: comprehensive architecture emulation if read-protected

Buffers

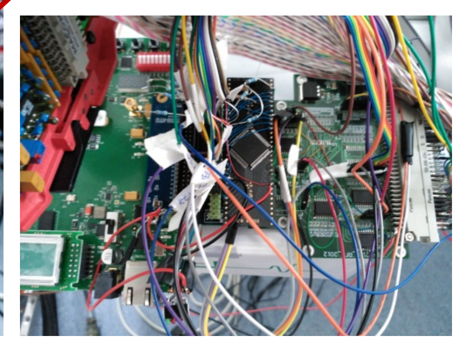
Cyclone III FPGA
(Altera Demo Kit)
PLDs read OK → VHDL
Embedded RAM, ROM

MC68SEC000



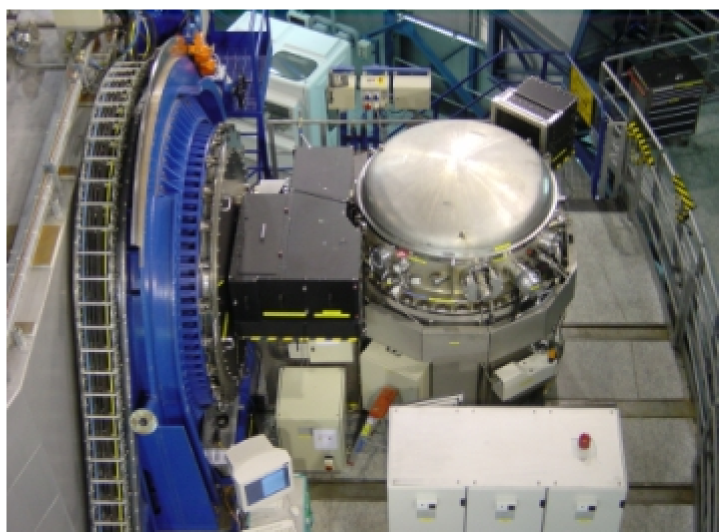
- Test OK
- PCB ongoing!

Buffers

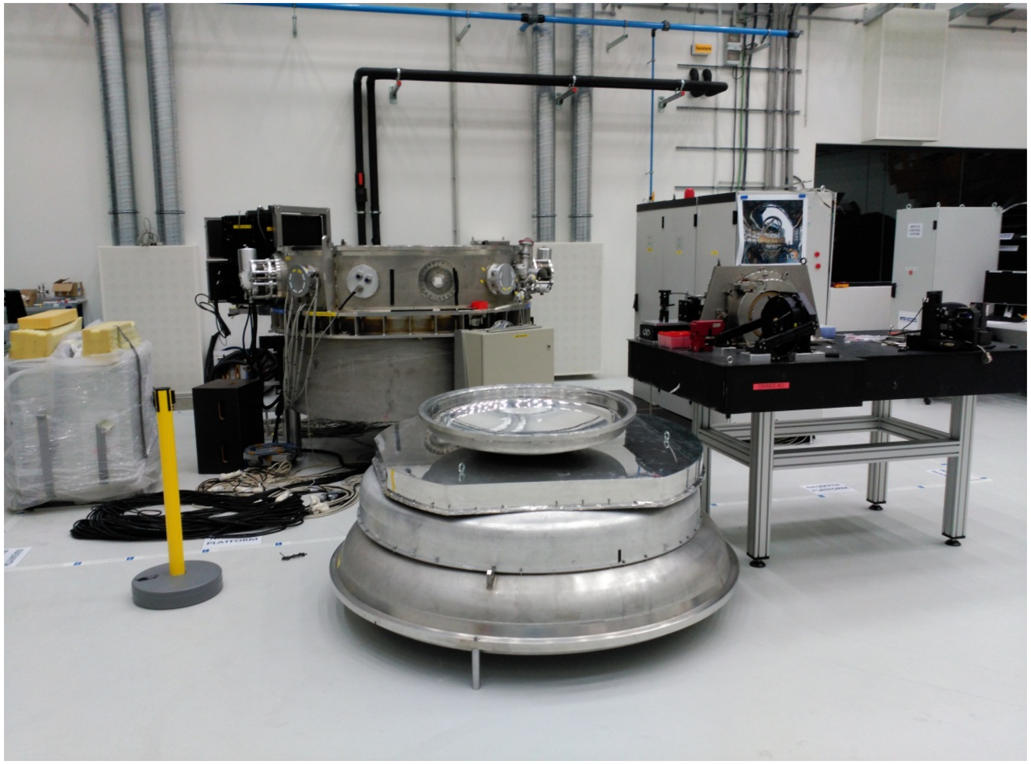


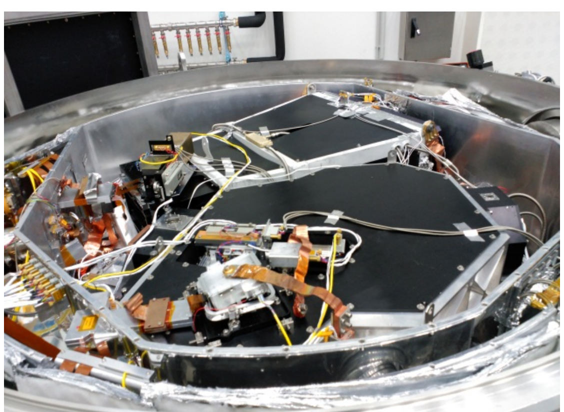
CRIRES+ (VLT CRIRES update)

- CRIRES (CRyogenic high-resolution InfraRed Echelle Spectrograph):
  - Cryogenic instrument
  - High vacumm (pumps)
  - Several motorized functions
  - Three cabinets to control the instrument + software
  - MACAO (Multi-Applications Curvature Adaptive Optics) is used to optimize the signal-to-noise ratio and the spatial resolution
  - Currently at ESO HQ (upgrade in progress)
  - Important obsolescence issues need to be addressed:
    - It uses several of the motor controller boards previously described
    - Other critical components: 10 years lifetime for the upgrade has to be guaranteed



CRIRES at the integration hall (ESO HQ)





Thanks for your attention