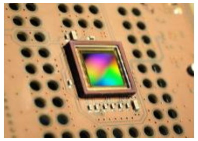
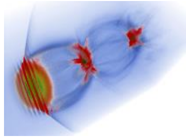
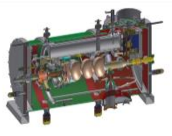






Highlights and Trends of Detector Instrumentation and Technology Development in Germany

Marc Weber

DTS

TWEPP-16
September 26, 2016
Karlsruhe, Germany

HELMHOLTZ ASSOCIATION

Research structures in Germany

Fraunhofer

- 24,000 employees
- 67 institutes
- Annual budget: 2.1 billion €

HELMHOLTZ | GEMEINSCHAFT

- 38,000 employees
- 18 research centers
- Annual budget: 4.4 billion €

MAX-PLANCK-GESELLSCHAFT

- 22,000 employees
- 83 institutes
- Annual budget: 1.8 billion €

Leibniz-Gemeinschaft

- 18,000 employees
- 89 institutes
- Annual budget: 1.7 billion €

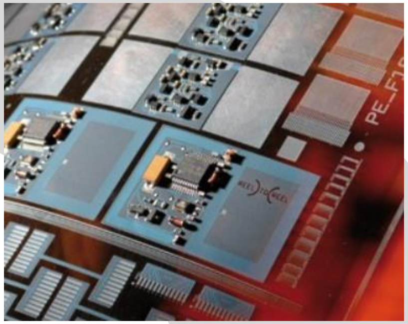
HELMHOLTZ | ASSOCIATION

Institutes you will know are …

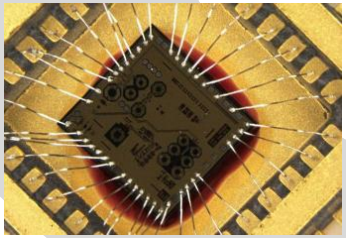
Fraunhofer IZM

CiS Forschungsinstitut für Mikrosensorik GmbH

Fraunhofer EMFT

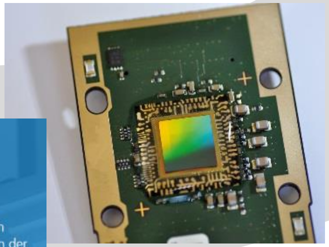


ihp
innovations for high performance microelectronics
Leibniz-Institut für innovative Mikroelektronik



MAX-PLANCK-GESELLSCHAFT
MPI HLL

Fraunhofer IMS



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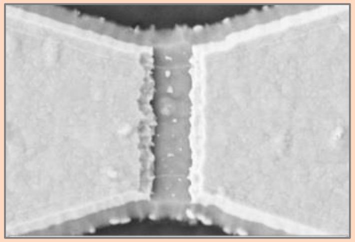
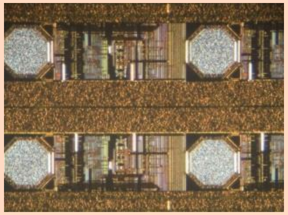
“Matter and Technologies”: ARD and DTS

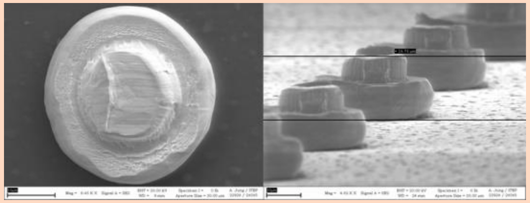
Sensors, ASICs and Interconnects



Sensors

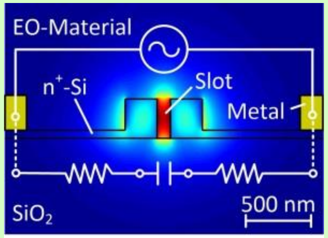


Readout Electronics



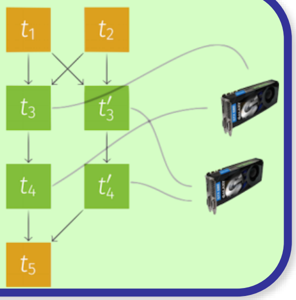
Interconnect, Packaging and Innovative Materials

Data Transmission and Processing



Terabit/s Optical Data Transmission

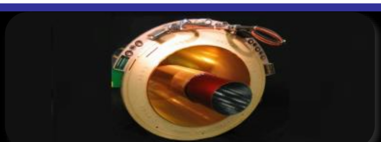
Intelligent Programmable Electronics



Parallel Processing

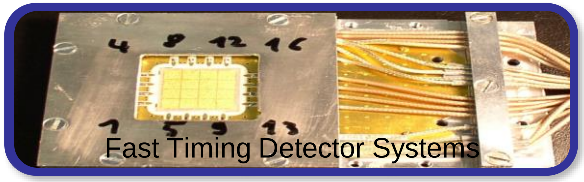
Detector Systems

HGF-Cube

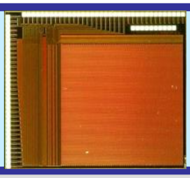


Compact Gaseous Detectors

Fast Photon and X-ray Detectors

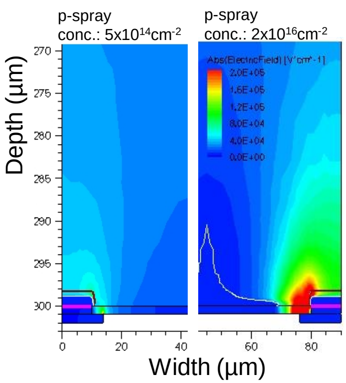


Fast Timing Detector Systems

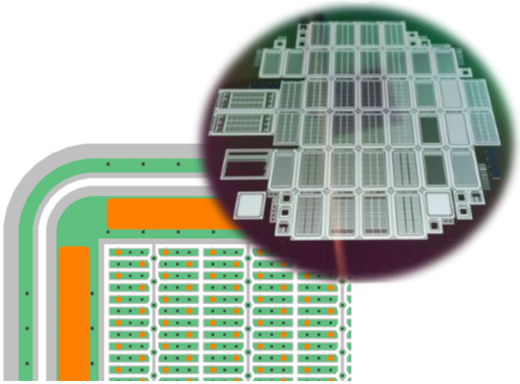


CMOS Sensor Systems

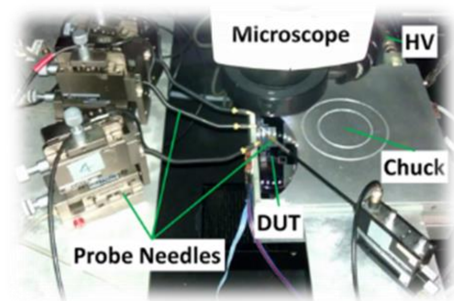
Silicon Sensor R&D



T-CAD device simulation
Layout and process optimization; radiation defect model development

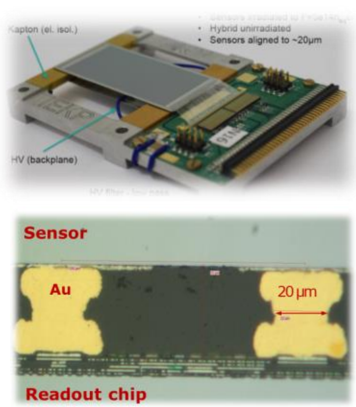


Sensor design
Mask layout in gds

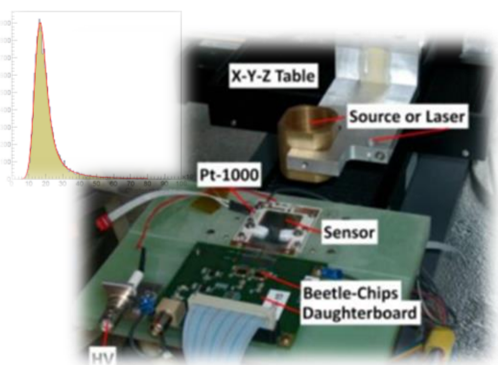


Electrical characterization
Micro-needle probe stations

Device irradiation
23MeV protons and x-ray available on site

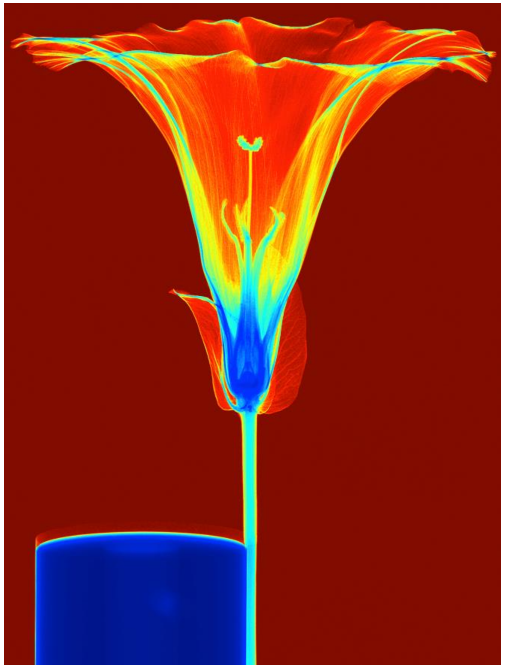


Assembly
Bump bonding, under-fill, spark protection, wire-bonding, precision gluing

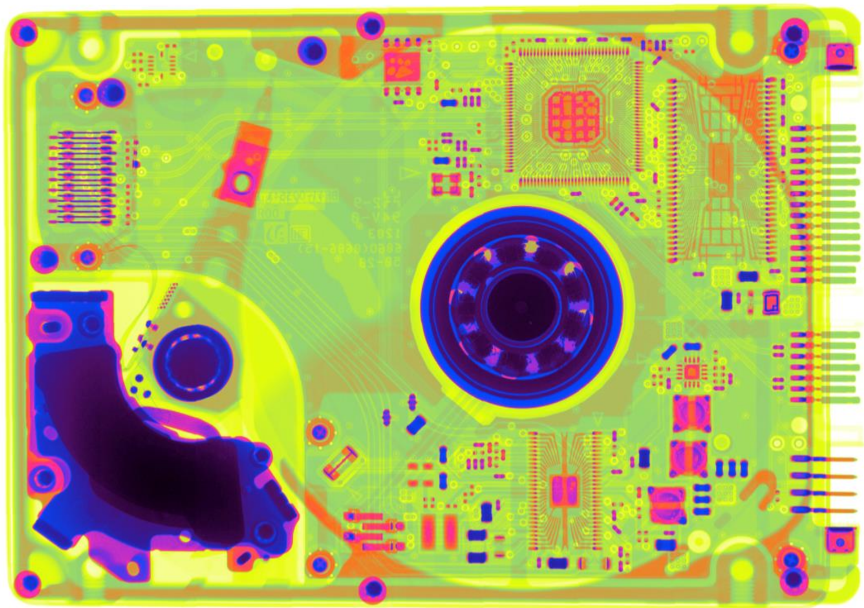


Performance studies
Read-out systems with particle and laser sources; beam tests

Soft materials and X-ray imaging



500 µm silicon sensors with Medipix3

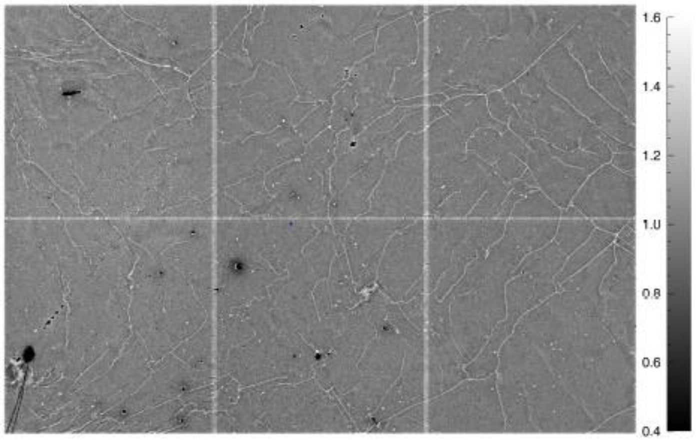


500 µm GaAs sensors with Medipix3

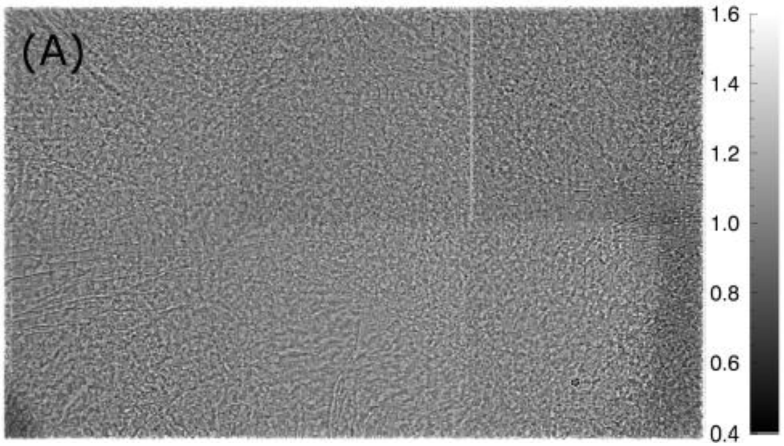
Courtesy Simon Procz, University Freiburg, KIT

Challenges of hetero semiconductors

Exposure of CdTe and GaAs sensors to 50 keV X-rays



6-tile GaAs sensor



6-tile CdTe sensor at 50

- These are cutting-edge devices!
- Critical for good detection efficiency beyond 12 keV (hard X-rays)
- CdTe sensors are important for CT scanners

From "The LAMBDA photon-counting pixel detector and high-Z sensor development", D. Pennicard et al., JINST 9 C12026 (2014)

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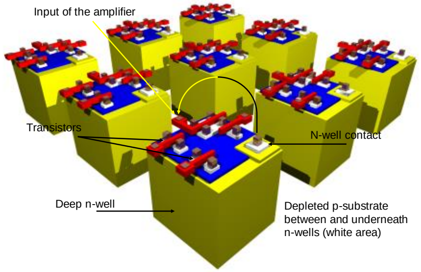
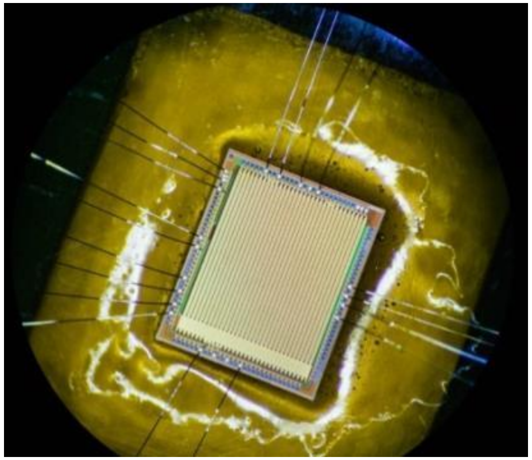
HV-CMOS development

- HV-CMOS is a new sensor structure developed at IPE by Ivan Peric
- In contrast to the standard CMOS sensor that use epi-layer and charge collection by diffusion, HVCMOS sensors rely on ionization and charge collection in the depleted region
- The pixel electronics is embedded inside the sensor diodes

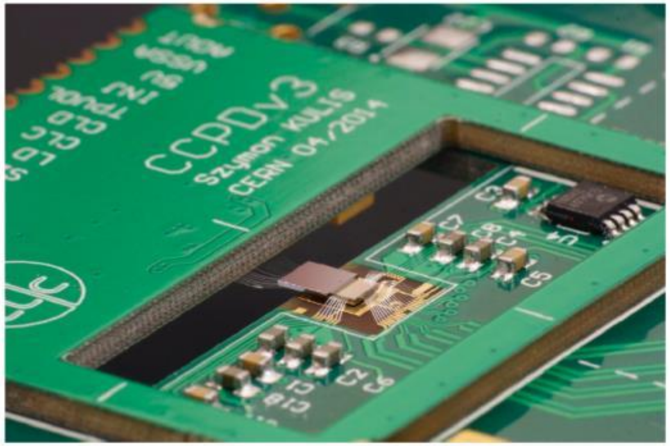


- HV-CMOS will be used in the Mu3e experiment at PSI
- HV-CMOS is an option for ATLAS and CLIC

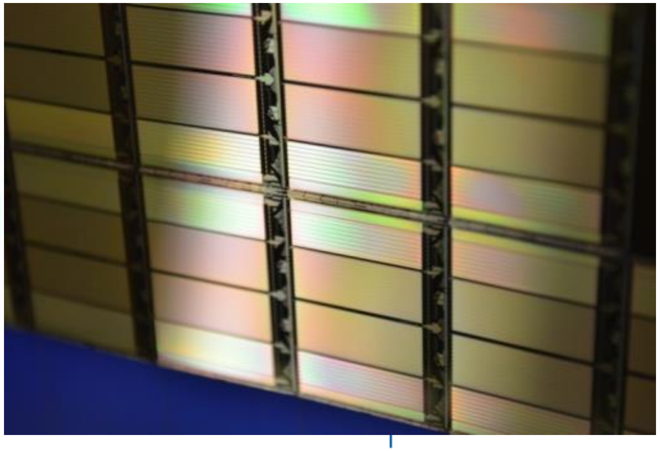
Mu3e-pixel prototype



CLICPIX CCPD



ATLAS pixel HVCMOS prototype



Low-cost bumping methods

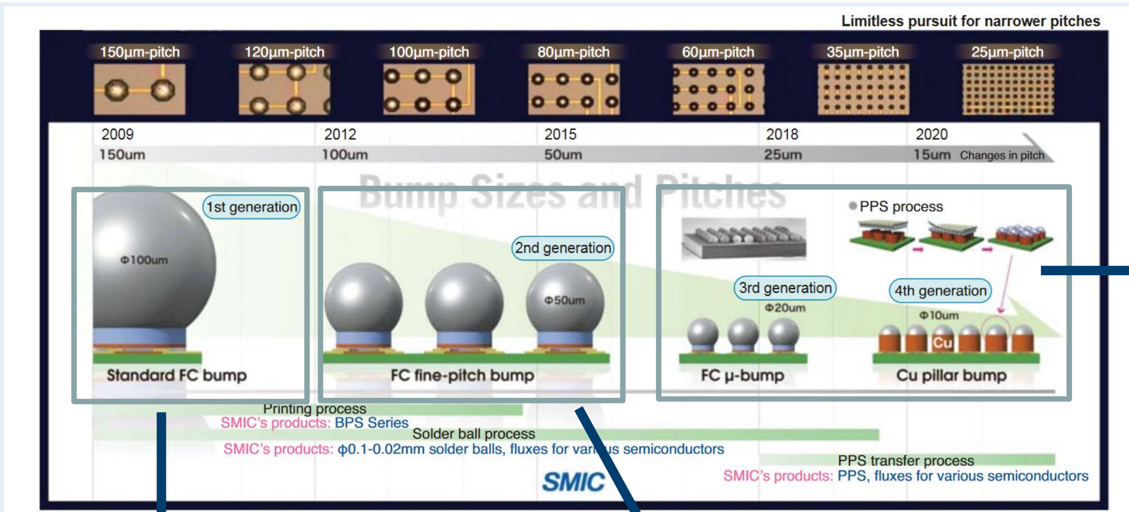
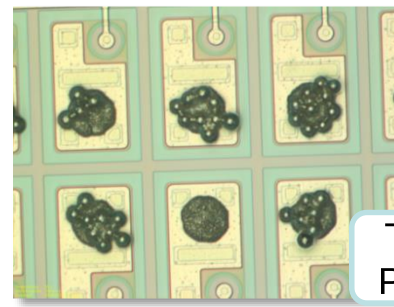


Figure: Roadmap of solder products for semiconductors

PPS (KIT)
min. diameter 10µm



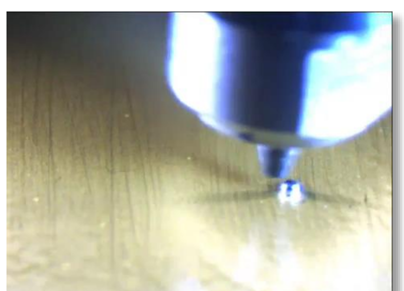
Transfer from Powder Sheet

Precoated by Powder Sheets

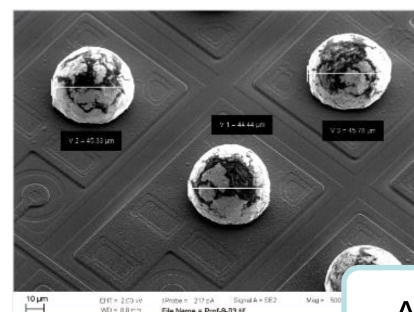
Stencil transfer
min. diameter 100 µm

http://www.ebay.de/itm/like/401009001648?lpid=106&chn=ps&ul_noapp=true

Jetting (DESY)
min. diameter 30 µm



https://www.youtube.com/watch?v=T5TUd83tOic



After reflow

KIT/IPE-AVT

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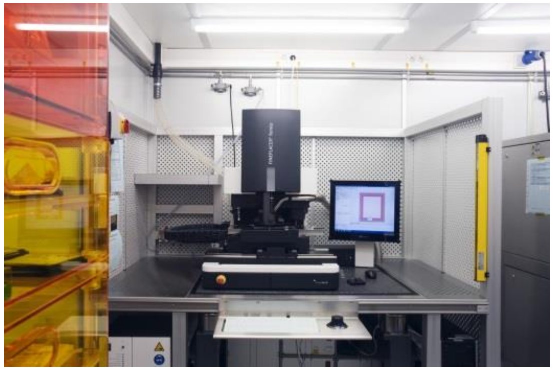
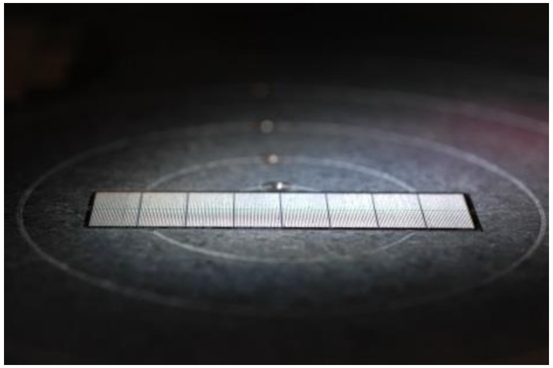
In-house flip-chip bonding at DESY and KIT

DESY process
Jetting and flip-chip bonding

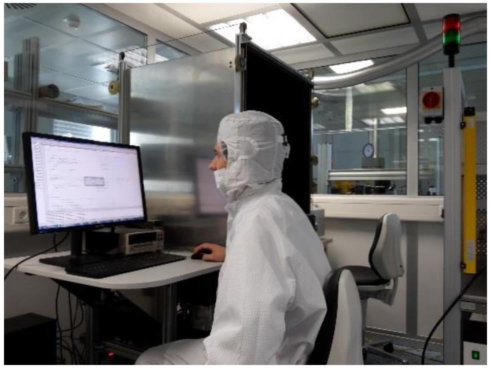
Pactech SB2 Jet



Finetech Femto

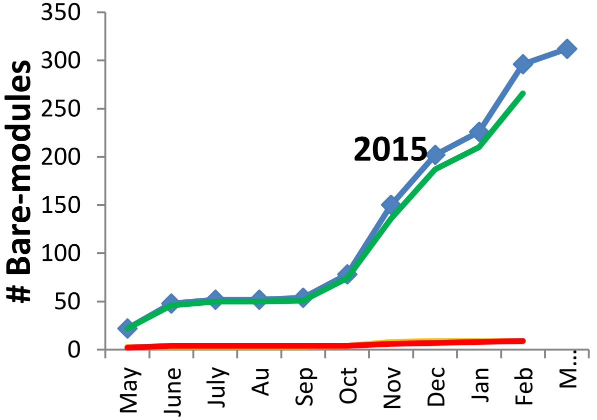


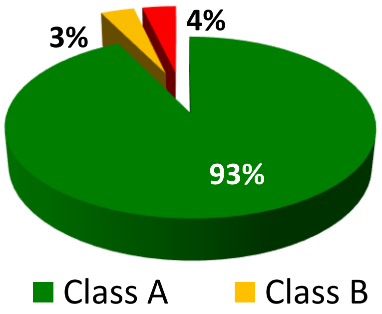
66'560 balls in 5 h



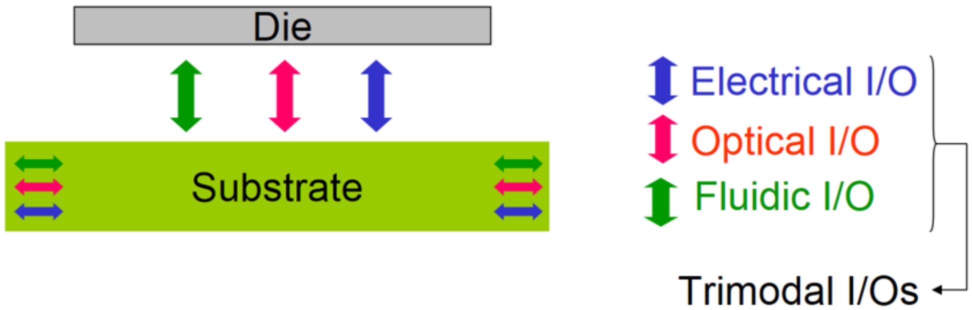
KIT process
Galvanic bumping (by RTI)
and flip-chip bonding

KIT CMS bare module yield

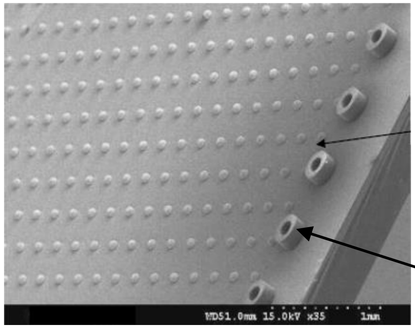




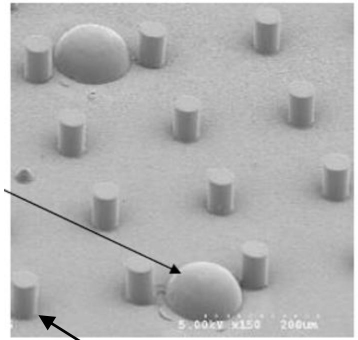
Combining novel packaging technologies



Electrical & Fluidic



Electrical & Optical



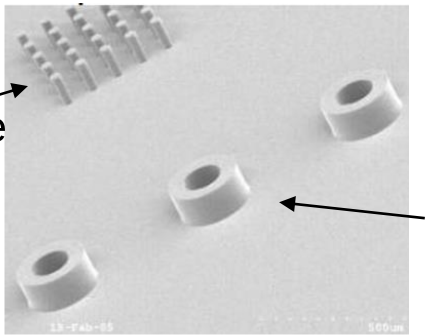
Extended wafer-scale fabrication

Electrical I/Os: Power and signal distribution

Optical I/Os: Massive off-chip bandwidth

Fluidic I/O: Heat removal

Optical & Fluidic



Examples from Georgia Tech: http://www.sematech.org/meetings/archives/3d/8334/pres/Bakir.pdf

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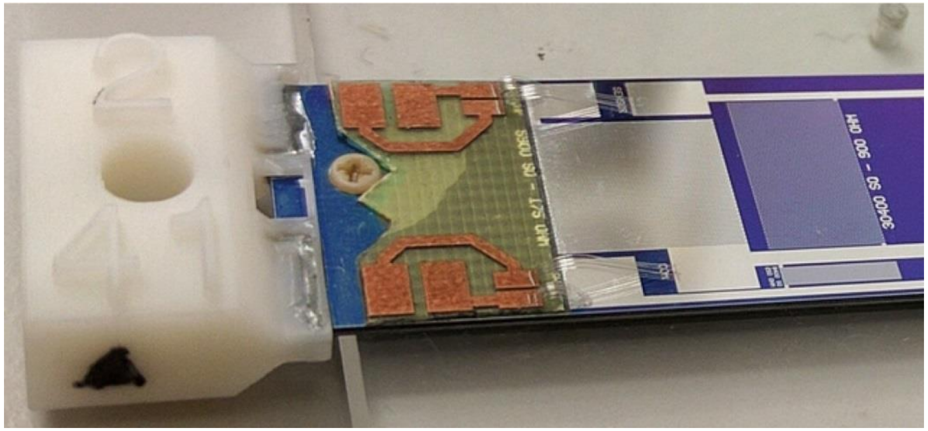
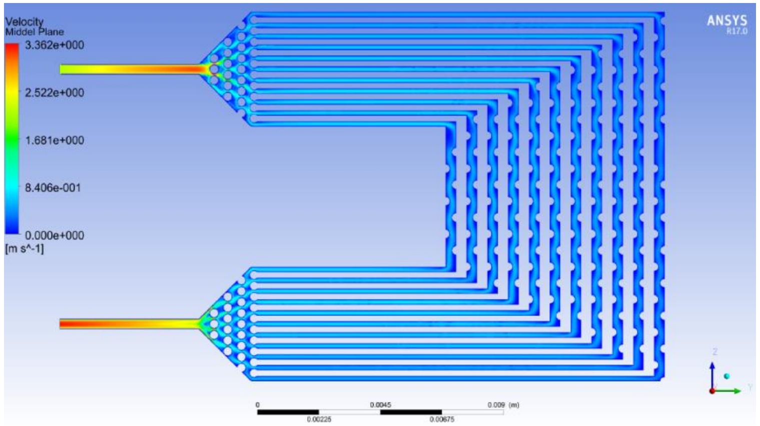
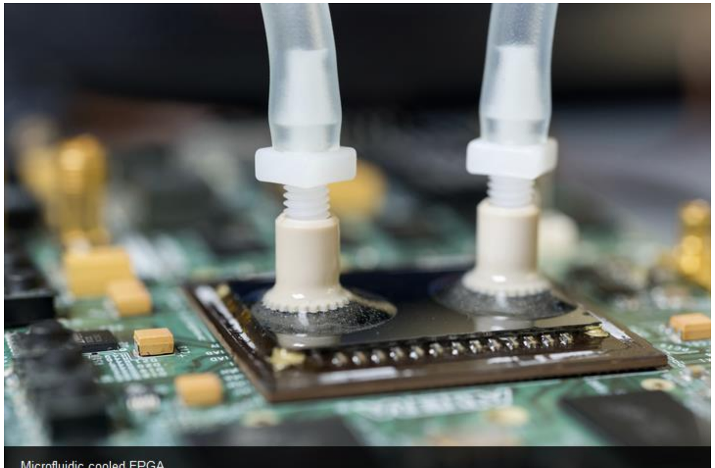
Examples relevant for particle physics





ILC-inspired prototype of micro-channel cooling (MPG Semiconductor Lab)
https://arxiv.org/abs/1604.08776


Microfluidic cooled FPGA

Micro-channel cooling of FPGAs (Georgia Tech)

28 nm Stratix FPGA with micro-etched back-side
http://www2.ece.gatech.edu/research/labs/i3ds/

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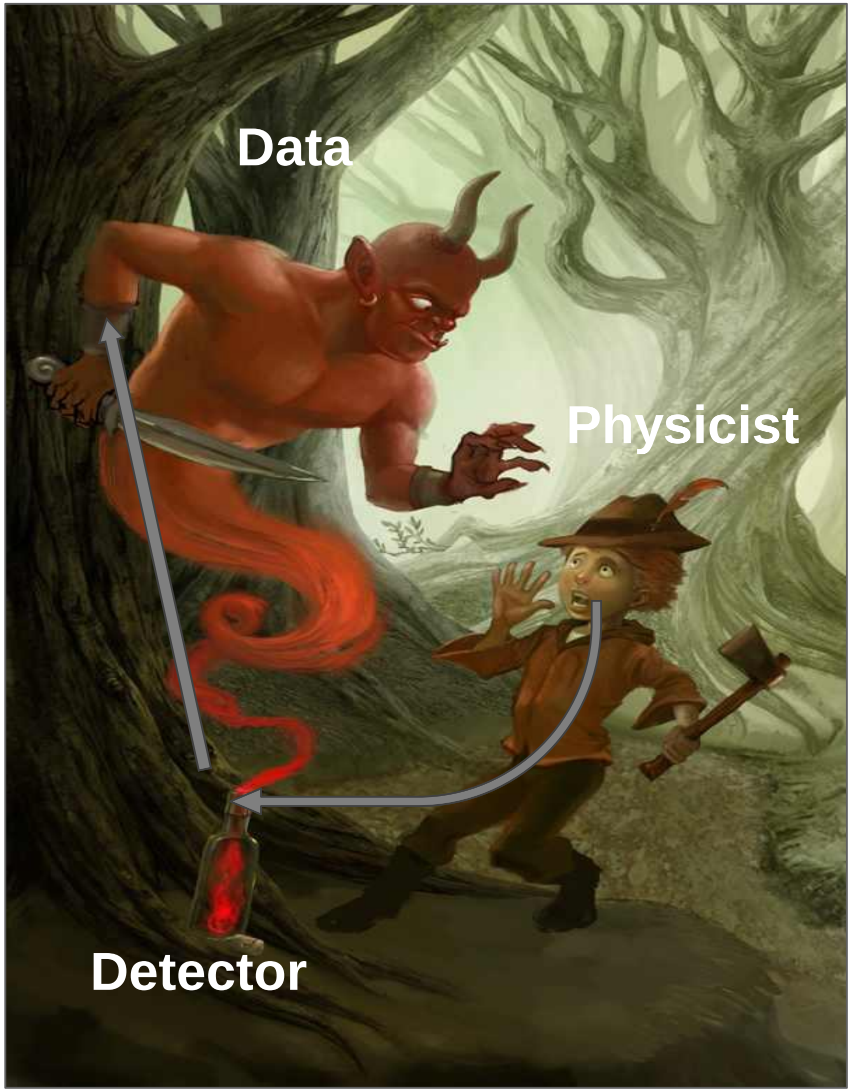
The „genie in the bottle“ or the data deluge

Grimm brothers

~ Pbit/s data
transmission

Data suppression
Local intelligence
Triggering



„HPC“ like computing
(e.g. FAIR experiments)
Triggering, filtering algorithms
On-line visualization

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CMS detector raw data
~3456 Pbyte/day

(1 Mbyte x 40 MHz)

se

htt

OLTZ
SOCIATION

Optical data transmission

- Optical data transmission as implemented in LHC experiments today is very powerful
- Getting there was a major effort and achievement, not only for the added challenge of radiation
- Our solutions differ from standard telecommunication in many ways and use on-off keying and laser diodes on the detector

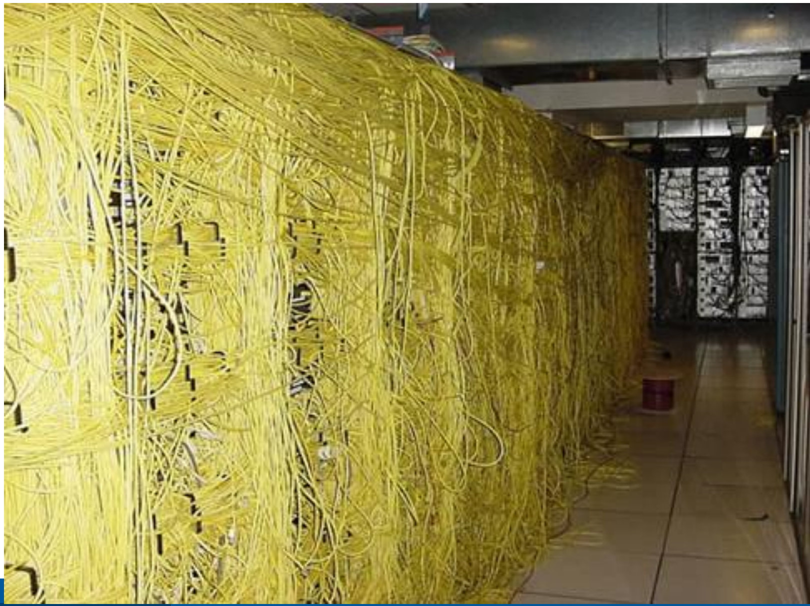
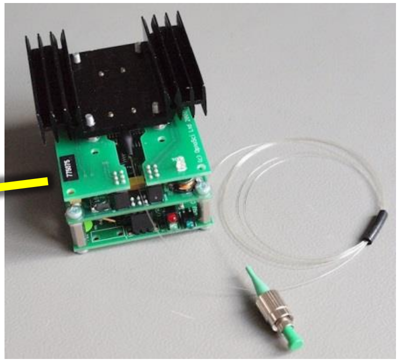


Photo of a row of racks with fiber optics in a random computing center

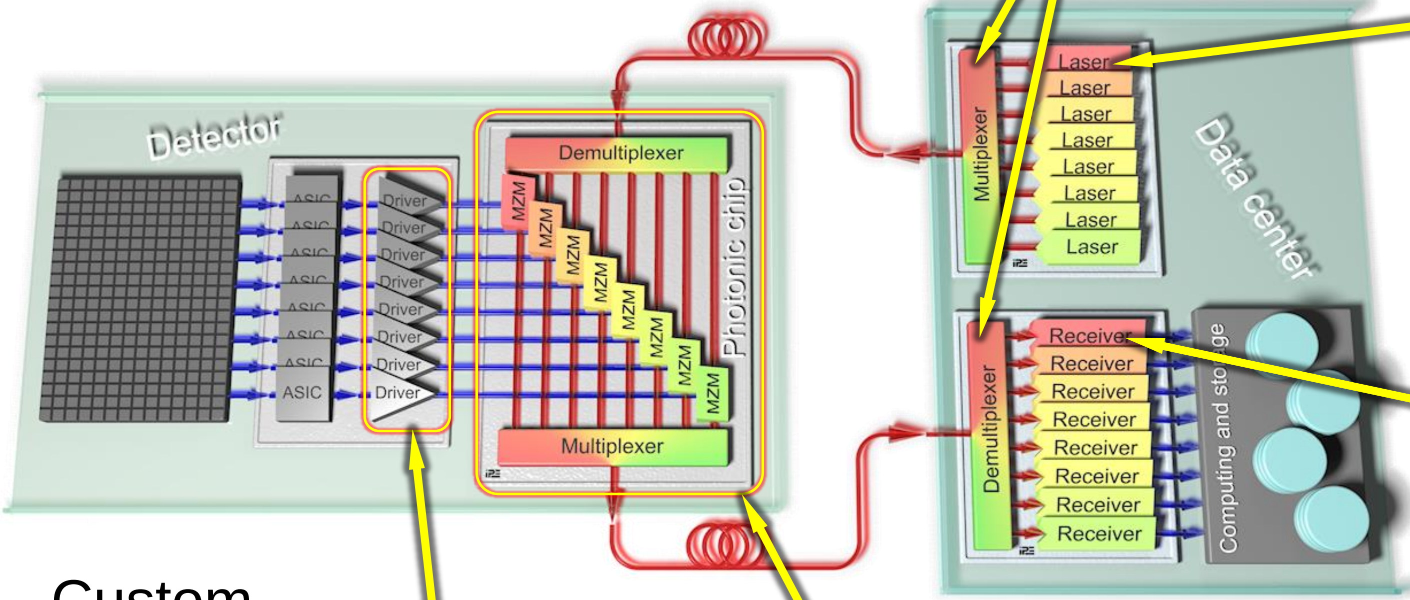
A future optical data transmission system for HEP

Telecom off-the-shelf components:

WDM-(de-)-multiplexer



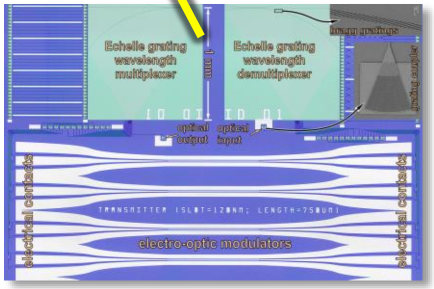
DFB lasers + drivers



Optical receiver

Custom built:

Modulator driver



Photonic integrated circuit: monolithically integrated wavelength division multiplexing (WDM) system

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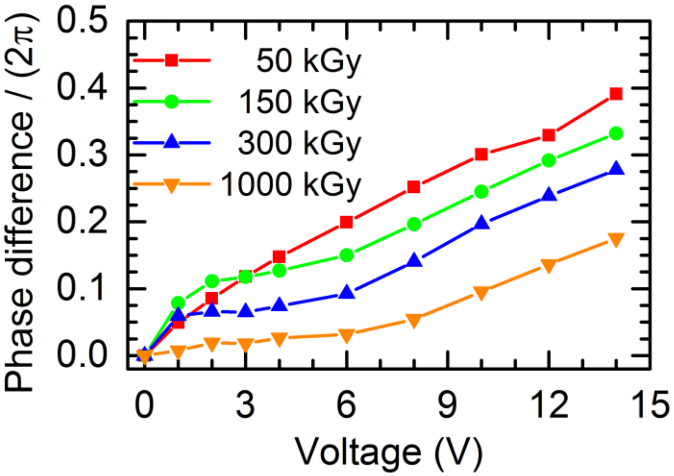
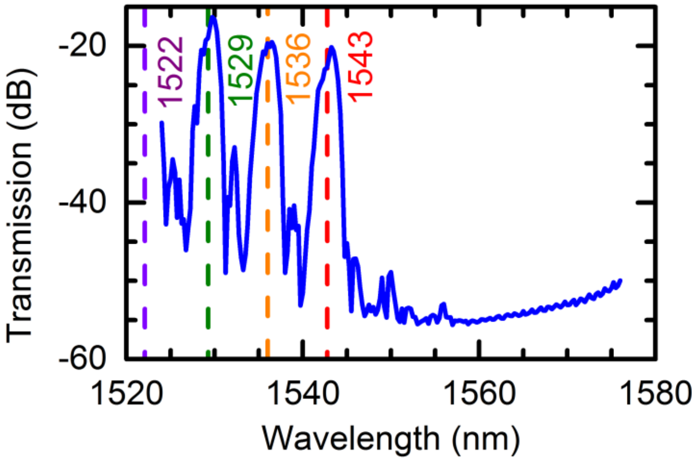
Glimpses at IPE activities for HEP

Long-term stable planar optical packaging using angle-polished fibers *(talk of D. Karnick)*



X-ray irradiation of pn-modulators:

- Operational after 1 MGy
- Shifted working point



First integrated WDM system:

- 4 channels
- More than 25 dB suppression ratio

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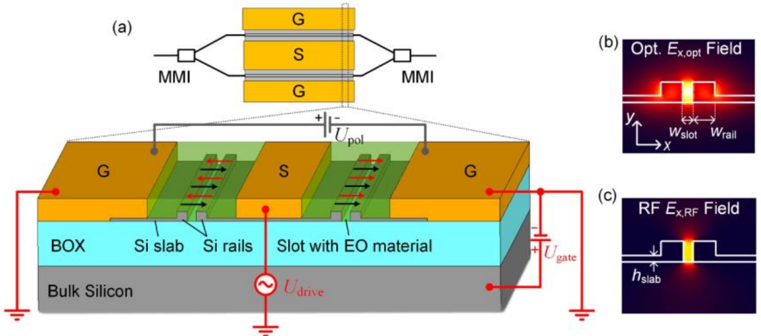
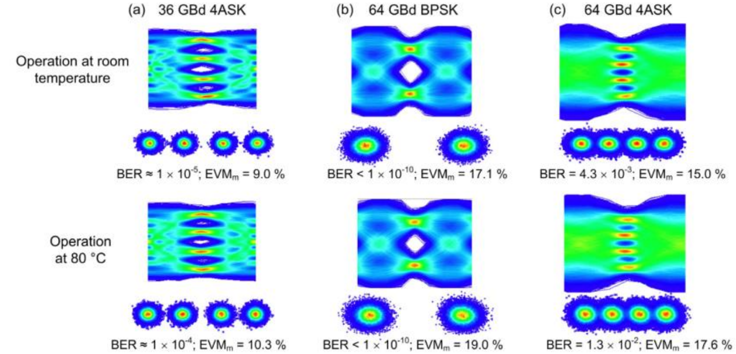
Research for telecom applications

Current basic research at the KIT-IPQ (Prof. Ch. Koos):

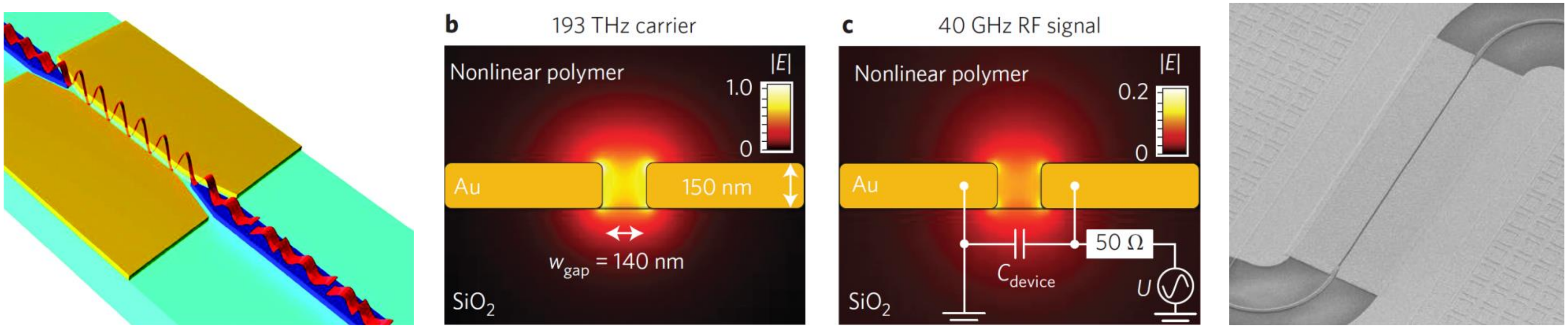
- Silicon-organic hybrid (SOH) modulator: 64 GBd, 4ASK signals, 80 °C





M. Lauermann *et al.*, “Generation of 64 GBd 4ASK signals using a silicon-organic hybrid modulator at 80 °C”, Opt. Express **24**, 2016, pp. 9389-9396, DOI:10.1364/OE.24.009389

- High-speed plasmonic phase modulators: short (29 µm), 65 GHz, 85 °C



A. Melikyan *et al.*, “High-speed plasmonic phase modulators”, Nature Photonics **8**, 2014, pp. 229-233, DOI:10.1038/nphoton.2014.9

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How could future systems in detector instrumentation look like?

- Ideally based on silicon photonics
- More complex keying schemes
- 5 – 100 times higher data rates i.e.   50 Gb/s – 1000 Gb/s on one fiber
- Highly integrated front-end

- Significant overhead off-detector
- It will not be cheaper than today

Optical systems: components and tasks

Laser source

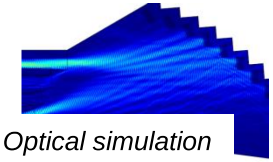

Laser drivers

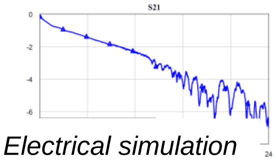
DFB lasers


WDM combiner

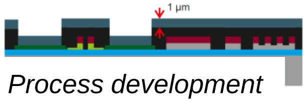

Control electronics

Photonic chip


Optical simulation



Electrical simulation



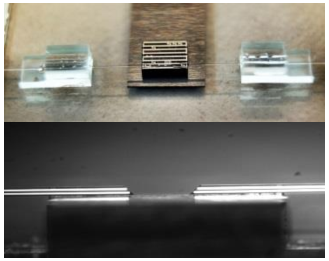
Process development

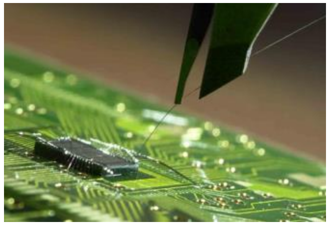

Chip layout

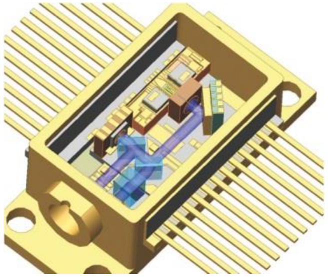

Chip fabrication


Characterization

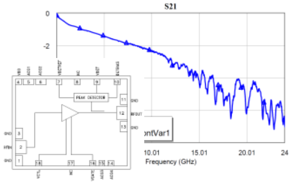
Packaging


Photonic packaging

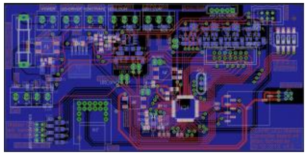

Electrical packaging


Mechanical housing

Modulator driver



Electrical simulation


Circuit design

Fabrication


Control electronics

Optical receiver


WDM splitter

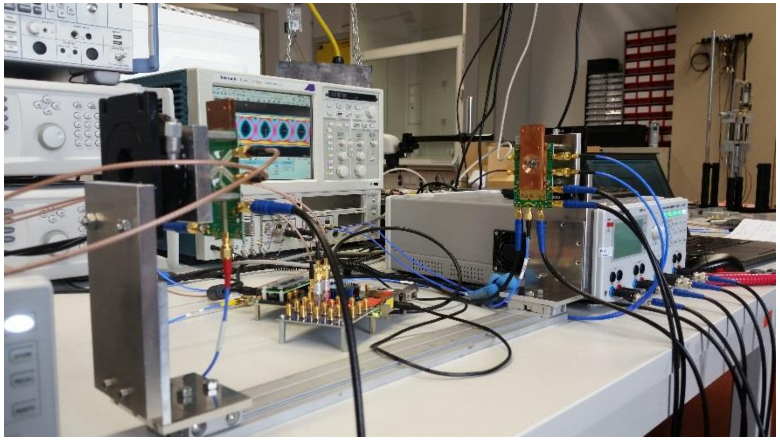

Receiver modules


Firmware development

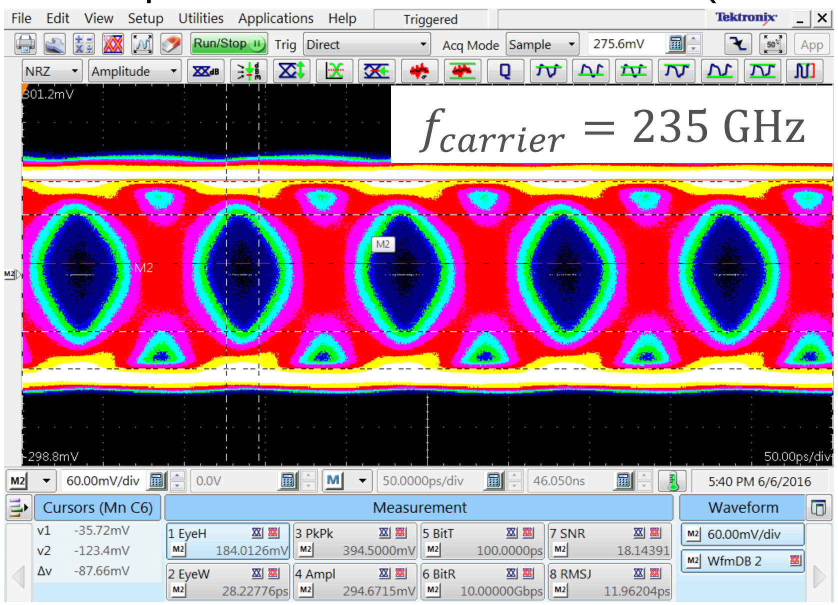
System development

240 GHz wireless data transmission

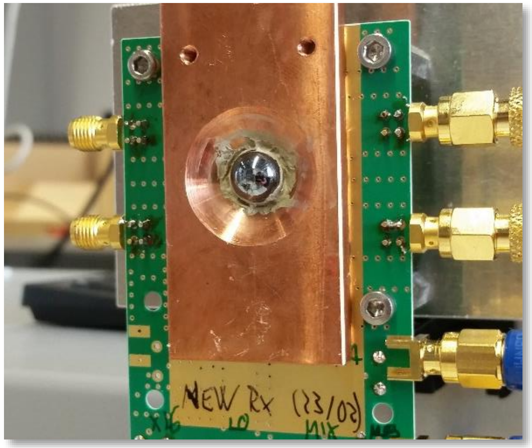
Setup in the laboratory at PI Heidelberg



10 Gb/s pseudo random data stream (PRBS7)



- Transmission distance ≈ 40 cm
- Silicon lenses G ≥ 25 dBi
- Binary Phase Shift Keying



Data rate [Gb/s]	Bit error rate
8.0	$\leq 5 \cdot 10^{-13}$
10.0	$3 \cdot 10^{-14}$
12.0	$5 \cdot 10^{-10}$

Courtesy A. Schönig
U. Heidelberg

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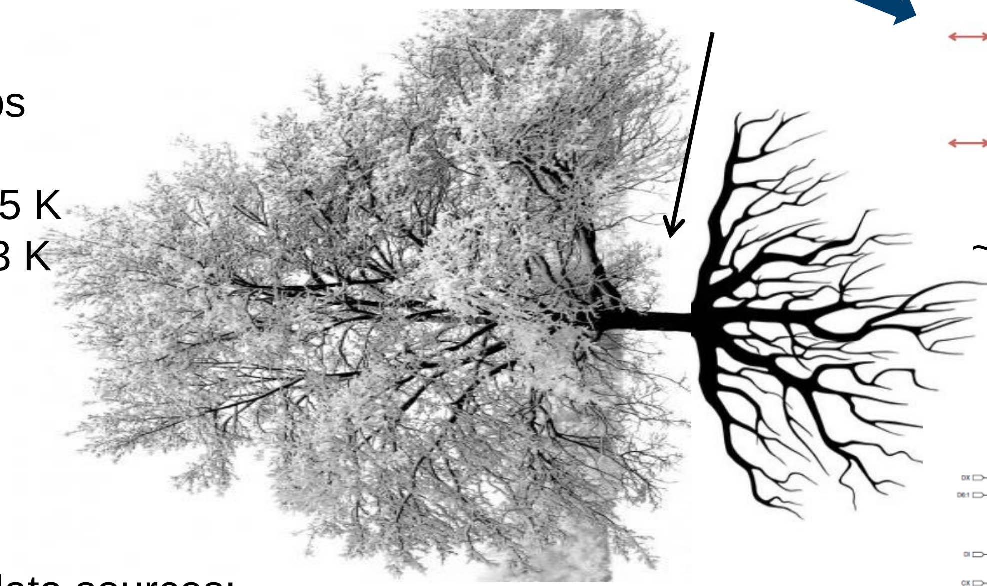
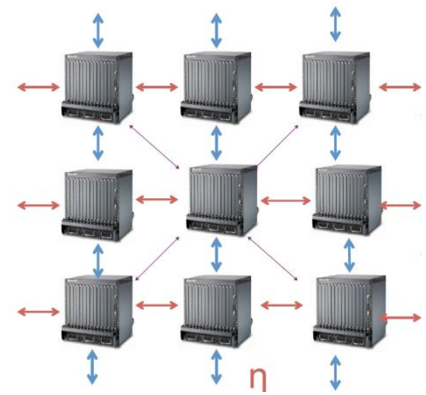
Track triggering systems (HL-CMS)

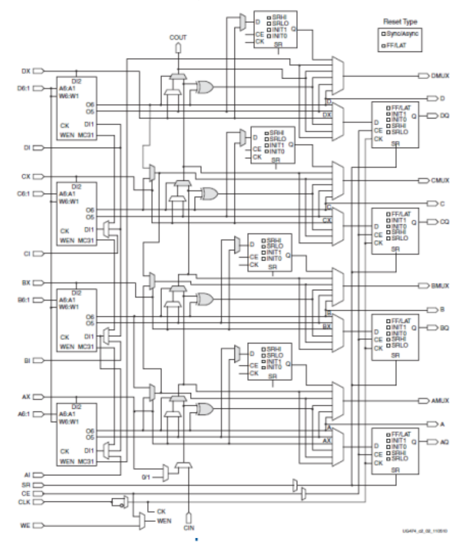
Number read-out chips (ROCs)
Strips ROC (CBC): ~135 K
Pixel ROC (MPA): ~113 K



Optical links ~15 K



~48 TT ATCA shelves

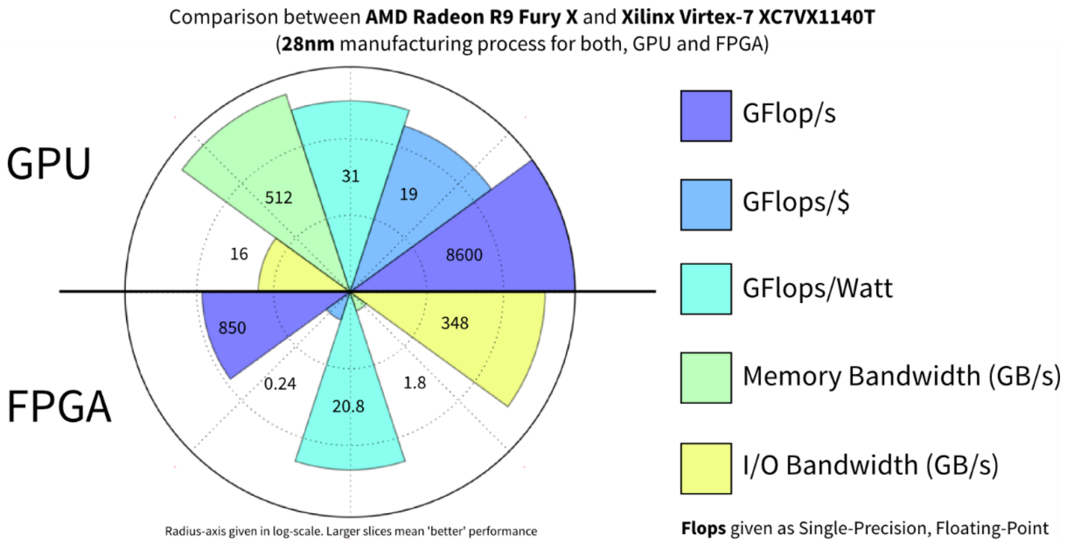


~ 200 m² of distributed data sources:
~47 M silicon strips (2S and PS)
~217 M silicon pixels (PS)

O(500 M) silicon pixels (inner tracker)

Look-up tables (Slices): ~500 M

Comparison: GPU vs FPGA



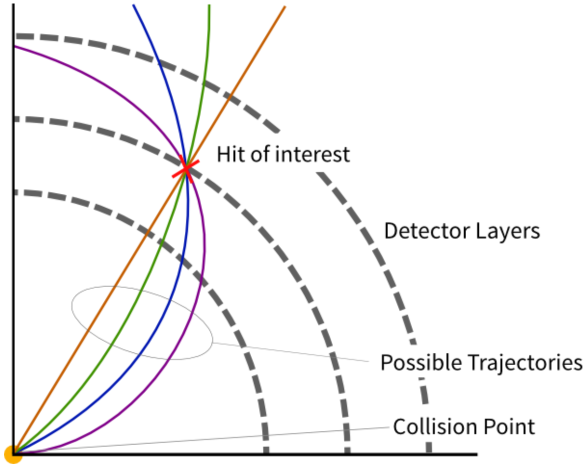
GPU Features
Rapid development cycles and high flexibility
Large bandwidth to external memory
High Floating-Point performance

FPGA Features
Huge I/O bandwidth
Deterministic timing/runtimes
High bit-level processing performance

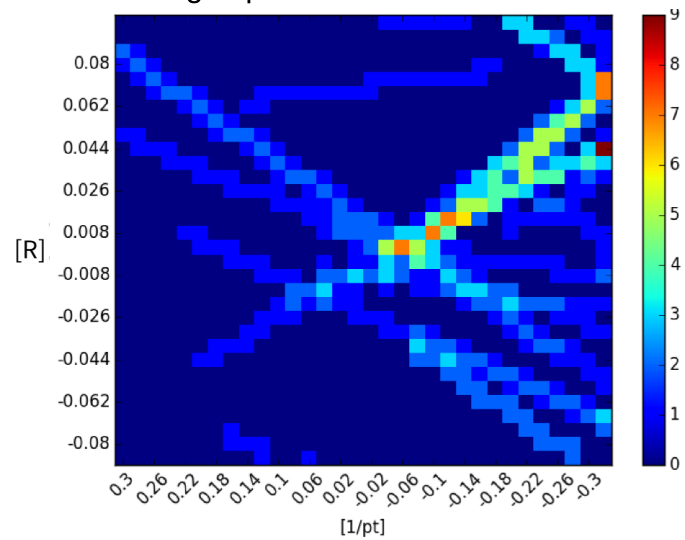
- Combination of GPU and FPGA is very promising, new tools are coming up

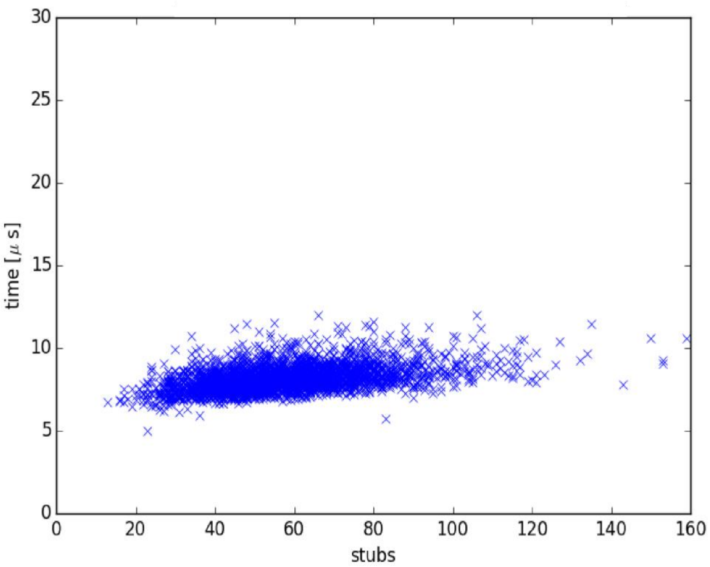
Hough transform on GPUs

Hough transformation concept



Hough space





- Idea: Transform hits into Hough space and search for intersections of hits in R-phi
- Algorithm implemented in GPU is identical to FPGA approaches
- Preliminary results show surprisingly good performance of GPUs

(talk of H. Mohr)

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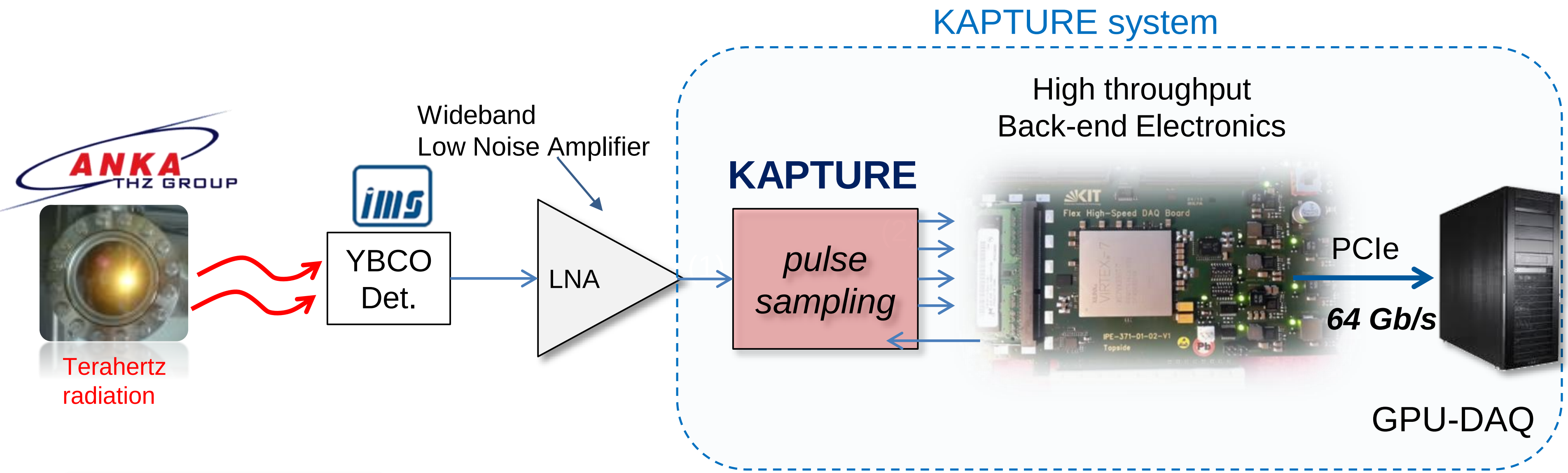
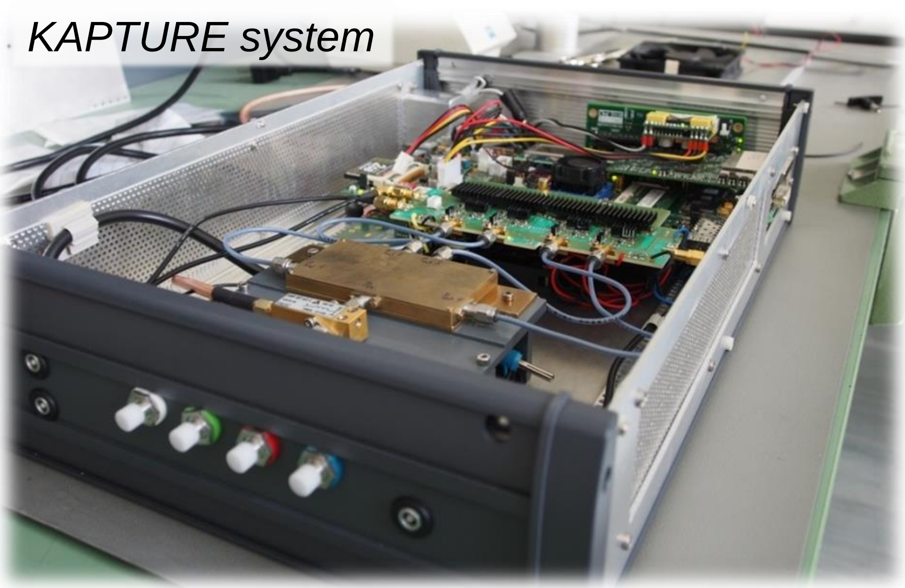
Ultrafast THz readout system





- Flexible pulse rate from 0.2 to 1.8 GHz
- Up to 8 samples by combining two KAPTURE boards
- Single-channel mode offers continuous 7.2 GS/s wave form sampling
- Mechanically/electrically compatible with FMC / µTCA system

(talk M. Caselle)

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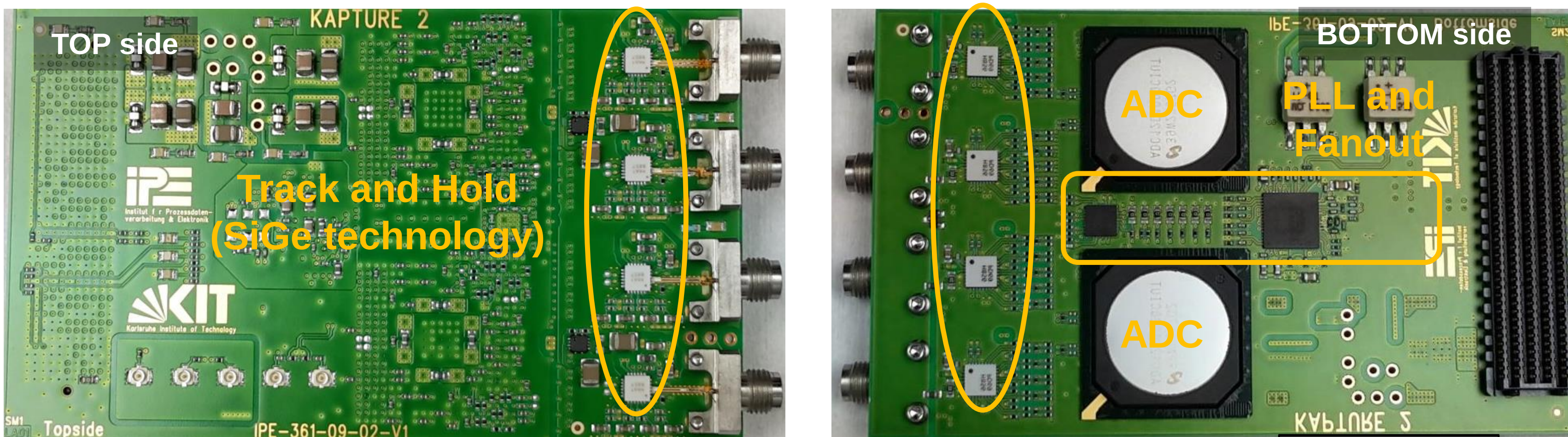
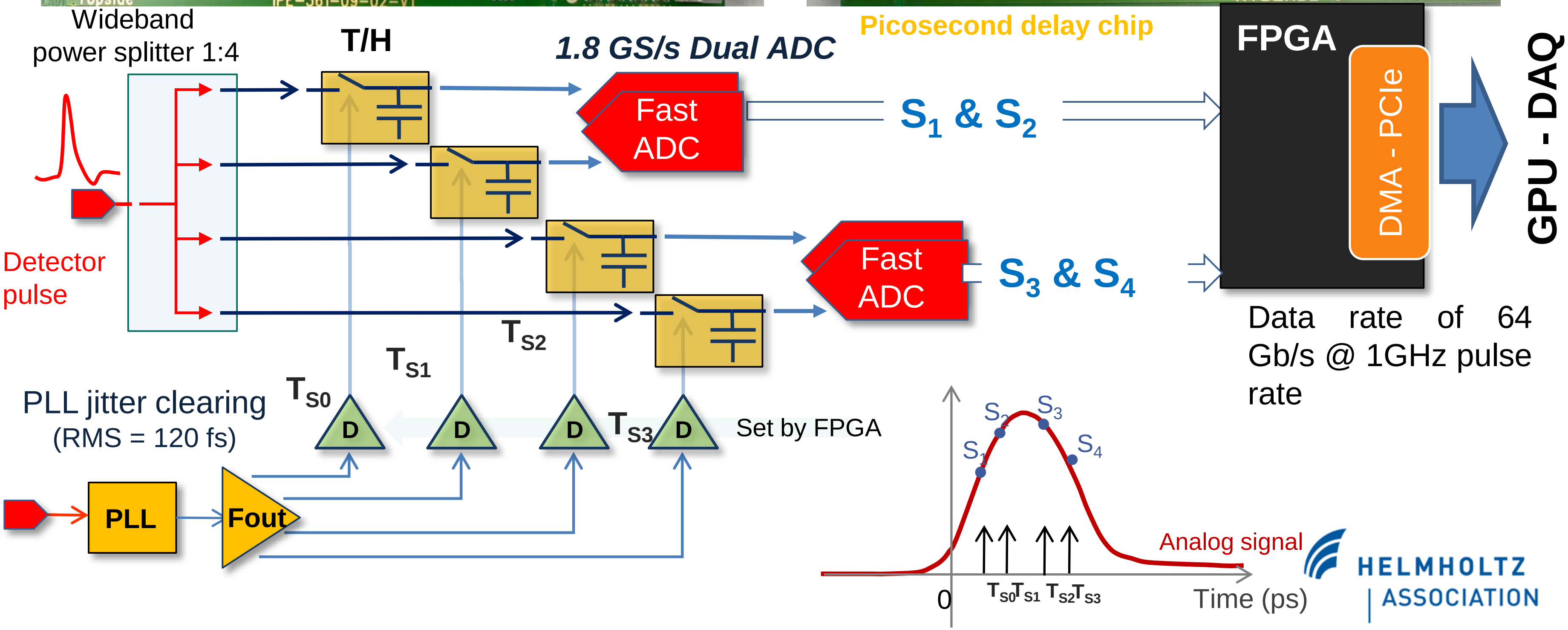
KAPTURE-2: ps-sampling architecture





Data rate of 64 Gb/s @ 1GHz pulse rate

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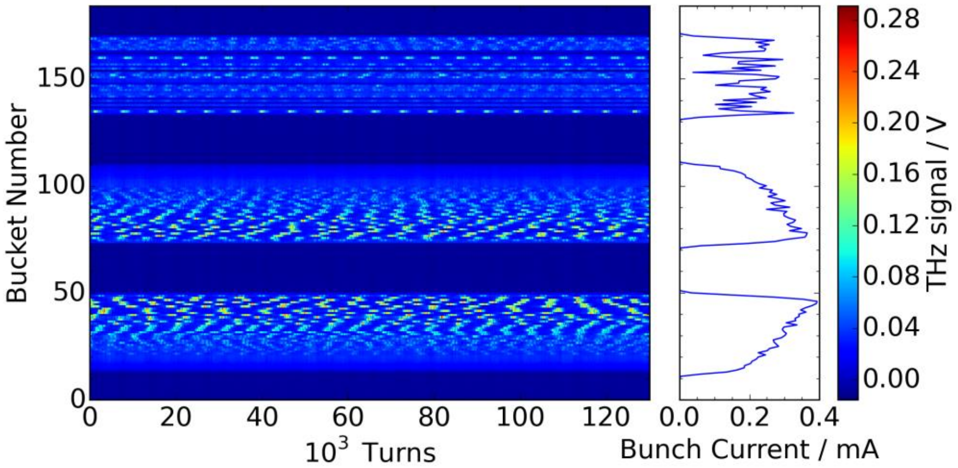
Observation of THz bursting thresholds



Simultaneous acquisition of all buckets turn-by-turn in streaming mode

M. Caselle, et al *Commissioning of an Ultra-fast Data Acquisition System for Coherent Synchrotron Radiation Detection*. 29/01/2015.

M. Caselle, et. al. *Picosecond Sampling Electronics for Terahertz Synchrotron Radiation.* 28/04/2015

M. Caselle, et al. *A Picosecond Sampling Electronic “KAPTURE" for Terahertz Synchrotron Radiation.* 01/06/2015

S.A. Chilingaryan, M. Caselle et al. *Computing Infrastructure for Online Monitoring and Control of High-throughput DAQ Electronic*. 28/04/2015

M. Caselle, et al. *Picosecond Sampling Electronics for Terahertz Synchrotron Radiation.* 06/01/2015

M. Brosi, M.Caselle et al. *Fast Mapping of Terahertz Bursting Threshold and Characteristic at Synchrotron Light Source.* 02/05/2016,

J.L. Steinmann, M. Caselle, et al. *Influence of Filling Pattern Structure on Synchrotron Radiation Spectrum at ANKA.* 03/06/2016,

M. Brosi, M. Caselle, et al. *Online Studies of THz-radiation in the Bursting Regime at ANKA.* 04/07/2015

J.L. Steinmann, M. Caselle, et al. *Non-interferometric Spectral Analysis of Synchrotron Radiation in the THz regime at ANKA.* 04/07/2015

A.-S. Müller, M. Caselle, et al. *Studies of Bunch-bunch Interactions in the ANKA Storage Ring with Coherent Synchrotron Radiation using an Ultra-fast Terahertz Detection System.* 10/06/2013

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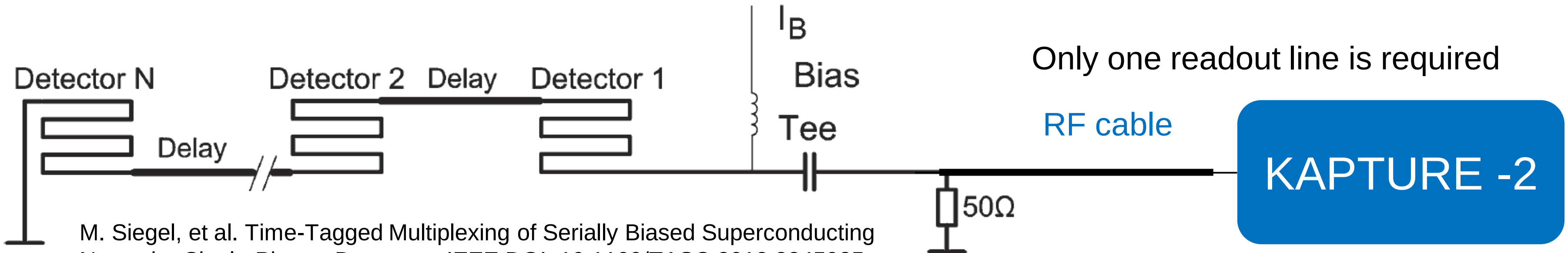
Multi-pixel THz readout scheme

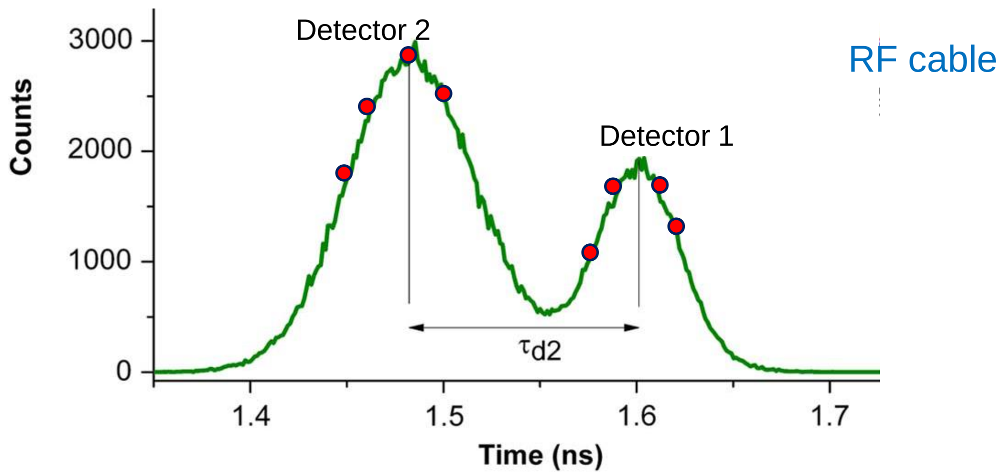
Multiplexing of Serially Biased Superconducting Nanowire Single-Photon Detectors

Only one readout line is required



M. Siegel, et al. Time-Tagged Multiplexing of Serially Biased Superconducting Nanowire Single-Photon Detectors. IEEE DOI: 10.1109/TASC.2013.2245935

Sampling points by KAPTURE



Designed to sample two ultrafast pulses at short time distance from 25 ps to 400 ps in 25 ps steps

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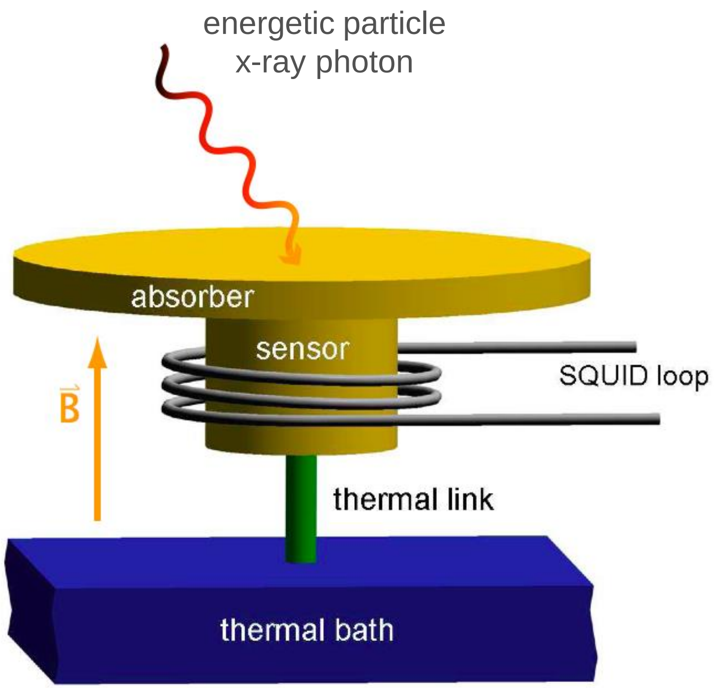
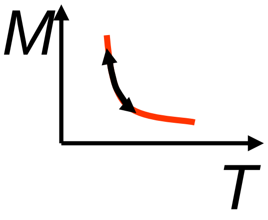
Metallic Magnetic Calorimeters (MMCs)



massive particle absorber

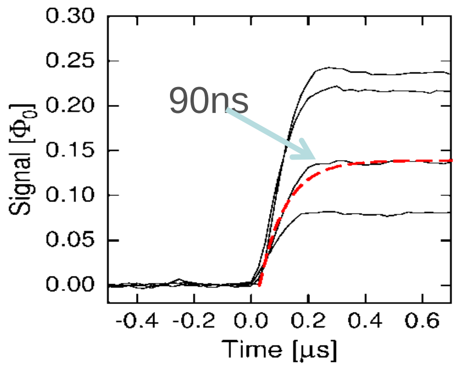
paramagnetic temperature sensor

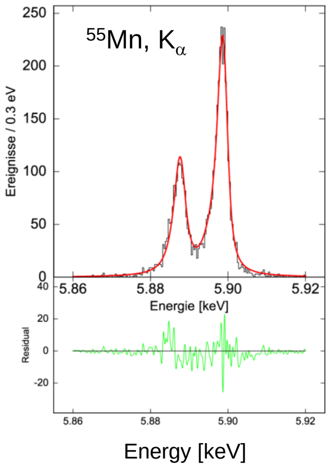


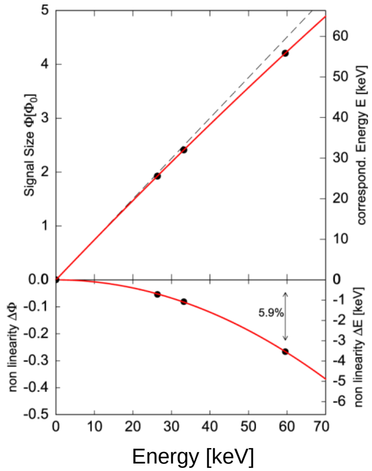
operation at low temperatures

- small specific heat
- large temperature change
- low thermal noise

Key features of MMCs

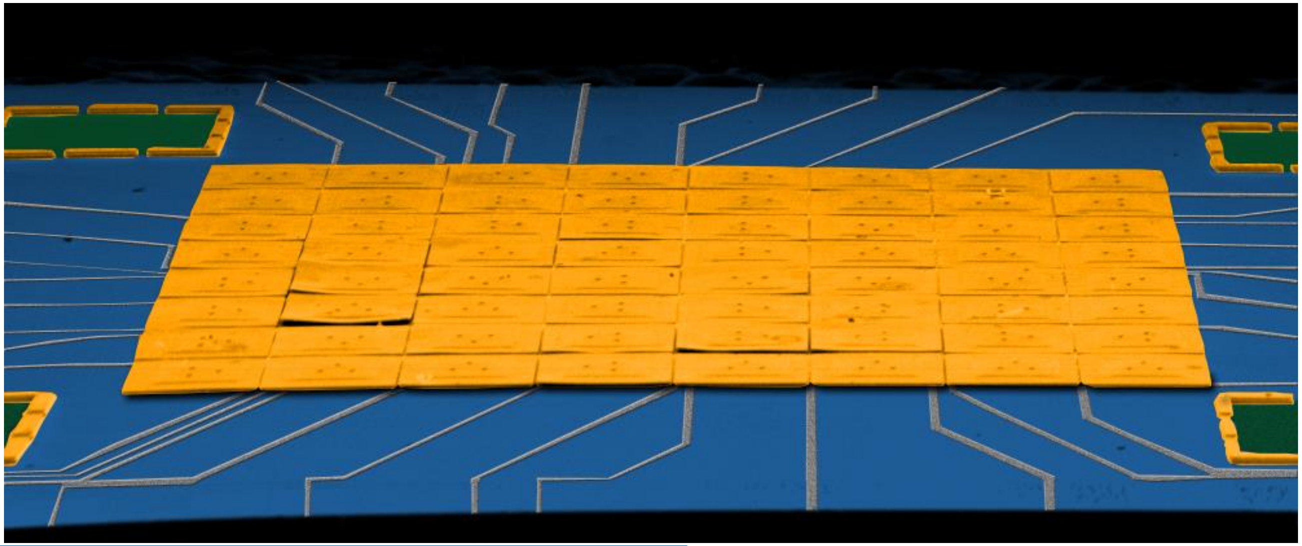






Unique combination of fast signal rise time, high energy resolution and very high linearity

Courtesy C. Enss, S. Kempf,
A. Fleischmann, U. Heidelberg



Applications

SSPDs and HEBs

- Telecommunications

  Quantum cryptography
- Terahertz imaging/astronomy
- Spectroscopy
- Security
- …

MMCs

- Astroparticle physics
- Photon science
- Astrophysics
- Atomic physics
- Materials research
- Metrology
- Nuclear forensics
- Quantum physics

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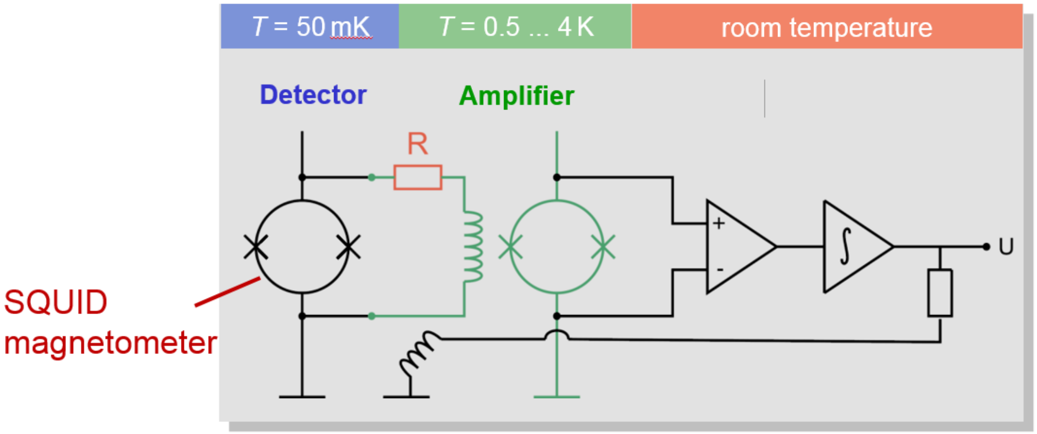
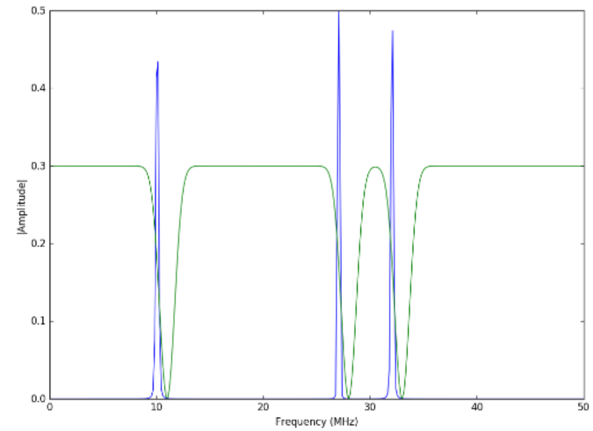
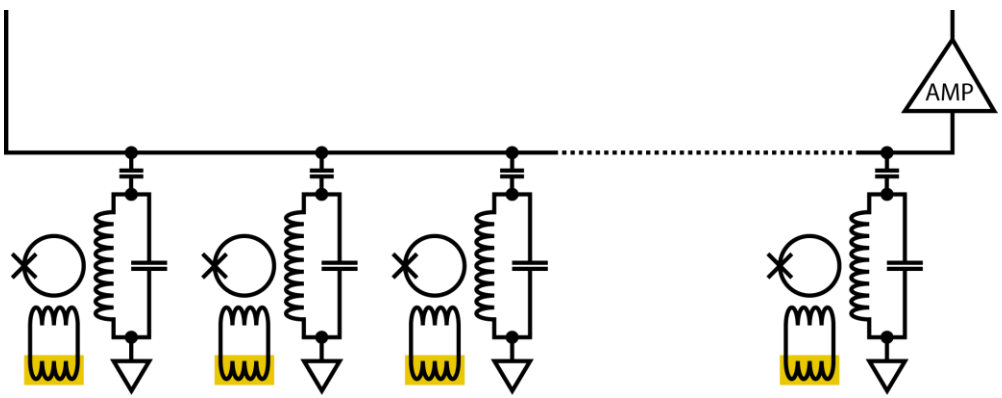
Readout of MMCs by frequency division multiplexing (FDM)





- Two-stage SQUID set up with flux locked loop to linearize the first stage SQUID
- Multi-pixel readout is challenging
- Superimpose microwaves on transmission line. Match each SQUID‘s resonance frequency, etc.



Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters, S.Kempf et al., J. Low. Temp. Phys. ***175*** *(2014) 850-860*

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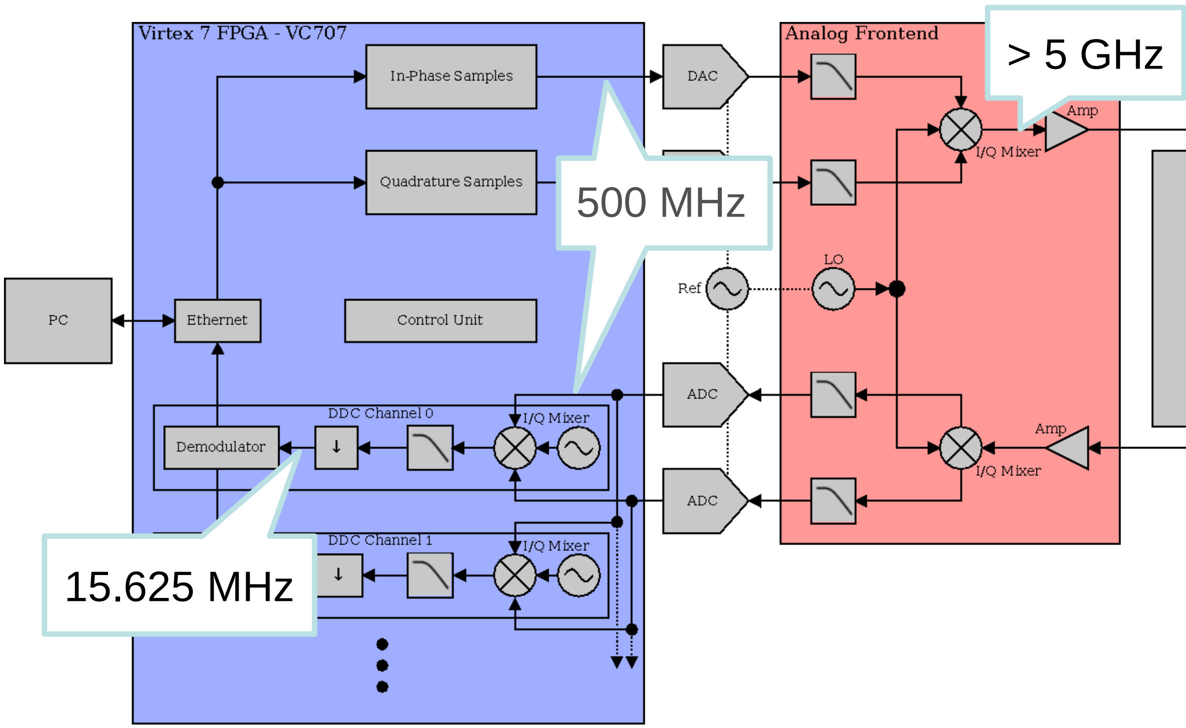
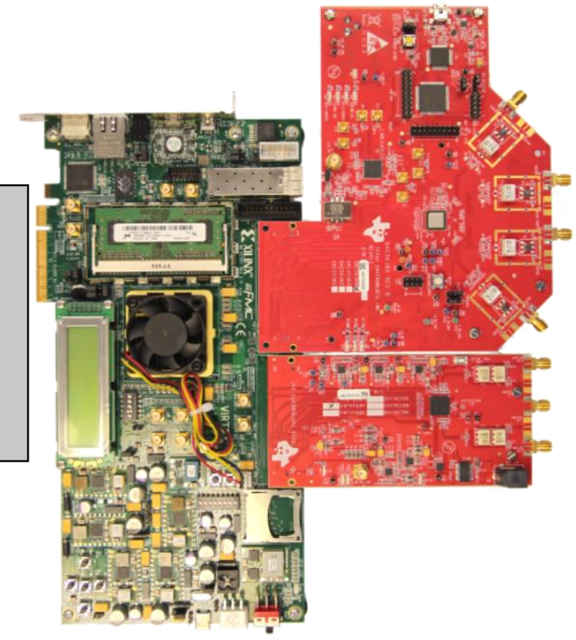
Software-defined radio





VC 707 Utilization	LUTs	BRAM	DSP
Peripherals	3.7 %	1.7 %	
One channel	1 %	0.74 %	0.29 %
Estimate for 64 channels	67.7%	49.1%	18.6%

DAC	ADC
2.5 GSPS	500 MSPS
16 Bit	16 Bit
Signal < 250 MHz	

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First experimental results

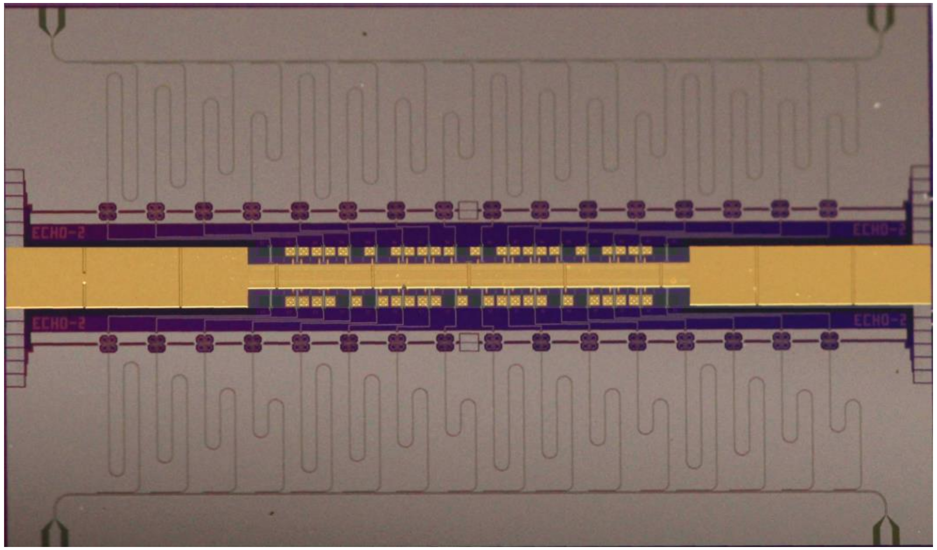


Photo of a multi-pixel MMC

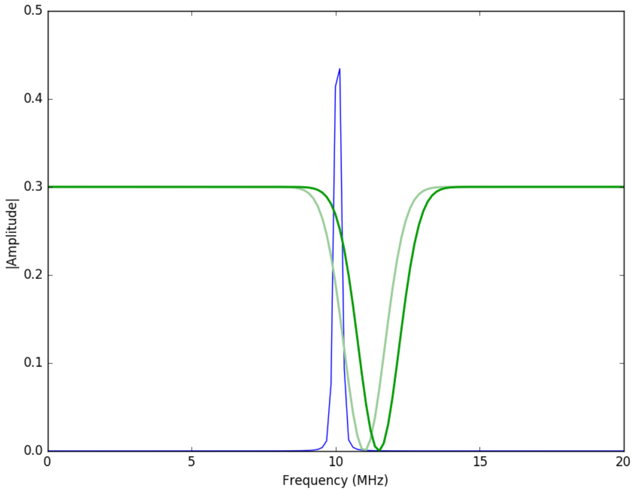
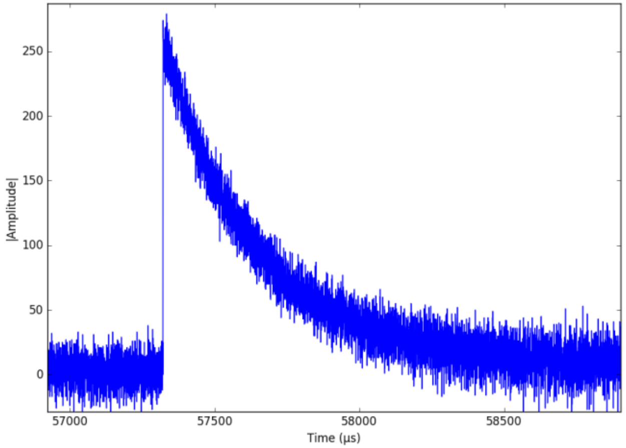


Illustration of the resonance shift due to a particle hitting the absorber



Measured, down-converted and filtered signal pulse

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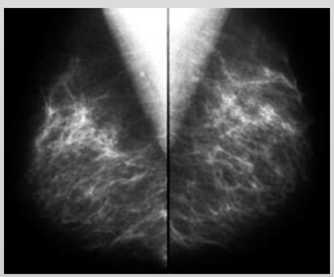
Breast cancer diagnosis

Today

Tomorrow

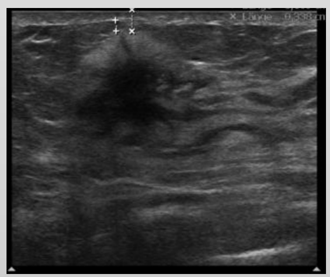
Mammography



- Screening
- Affordable

- 2D + Compression
- X-ray

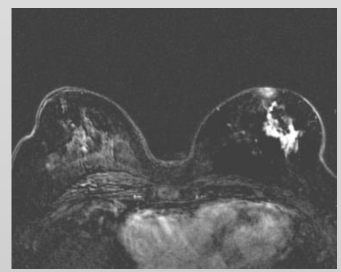
Sonography



- Widely available for additional imaging

- Not reproducible
- Limited sensitivity

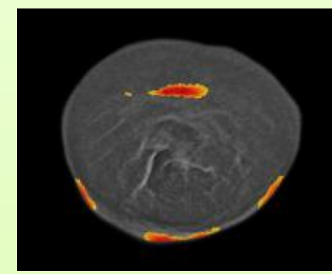
MRI



- High sensitivity and specificity

- Expensive
- Contrast agent

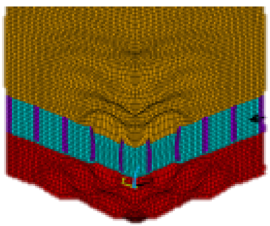
USCT



- As **good** as **MRI**?
- As **affordable** as **mammography**?
- As **harmless** as **sonography**?

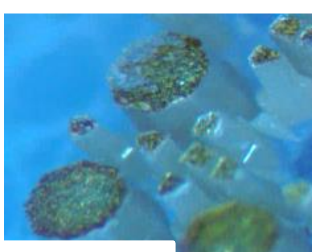
Societal benefit: Ultrasonic CT

Transducer development



Transducer design

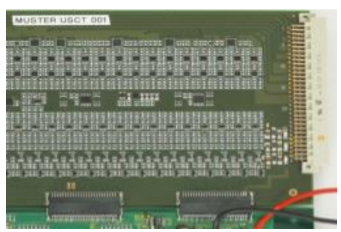
Electronics



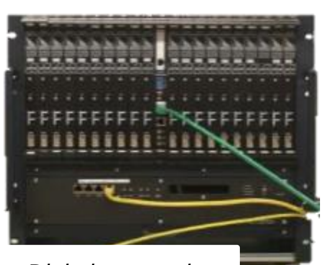
Transducer

Parallel data acquisition

Parallel channels



Electronics



Digital processing

Clinical applicability

Biocompatibility

3D reconstruction

Acceleration

Medical analysis

Analysis

Mittwoch, 14. Oktober 2015 — SÜDWESTECHO — Ausgabe Nr. 237 – Seite 9

Innovationspreis geht an Nicole Ruiter

Neue Methode zur Brustkrebs-Früherkennung

Von unserem Redaktionsmitglied Bernd Kamleitner

Baden-Baden. Mit einer neuen Methode zur Brustkrebs-Früherkennung hat Nicole Ruiter mit ihrem Team vom Institut für Prozessdatenverarbeitung und Elektronik am Karlsruher Institut für Technologie (KIT) den mit 20 000 Euro dotierten Innovationspreis NEO der Technologieregion Karlsruhe gewonnen. „Sie haben es verdient!", würdigte Deutschlands bekanntester Arzt Dietrich Grönemeyer gestern Abend bei der Preisverleihung in Baden-Baden.

Der Radiologe, ZDF-Moderator und Bestseller-Autor räumte als Laudator ein, dass ihm die Auswahl unter den fünf nominierten Projekten – die BNN haben alle in der gestrigen Ausgabe auf der Wissenschafts-Seite ausführlich vorgestellt – selbst schwer gefallen wäre: „Ich wüsste nicht, wofür ich mich entschieden hätte." Für ihn sei die Technologieregion nicht nur deshalb eine der innovativsten Regionen in Deutschland. Die neue Methode mit einer 3-D-Ultraschall-Computertomografie sei eine Idee mit hohem Entwicklungspotenzial, würdigte die Jury die Arbeit des Teams um die gebürtige Rastatterin. Das Verfahren sei genauer, weniger belastend für die Frauen und auch noch günstiger als die herkömmliche Früherkennungs-Methode. Bei der Röntgen-Mammografie wird die Brust sehr stark komprimiert, bei dem neuen Verfahren liegt die Frau dagegen mit dem Bauch auf dem Untersuchungsbett und legt die Brust in eine mit Wasser gefüllte Öffnung, den Messbehälter. Bislang ist das Gerät allerdings nur zu Forschungszwecken im Einsatz. Nicole Ruiter hofft jedoch auf eine baldige Zulassung.

Dietrich Grönemeyer führte aus, dass die Menschen in Deutschland trotz aller Fortschritte und Reformen nicht so gesund seien, „wie wir es gerne wären." 1,8 Millionen übergewichtige Kinder, 30 Millionen Menschen mit Bluthochdruck oder Rückenschmerzen schon bei Jugendlichen seien Beispiele dafür. „Die meisten Menschen wissen mehr vom Auto als vom Körper," so seine Erfahrung.

Der Radiologe engagiert sich schon seit vielen Jahren für Vorsorge und Aufklärung beim Thema Gesundheit. Sein Credo: „Wir sollten nicht nur punktuell, sondern permanent was für die Gesundheit tun." Medizinische Anwendungen und Vorsorge würden hierzulande allerdings oft nur als Kostenfaktor betrachtet, bei dem „jeder Euro irgendwie weh tut". Das ist für den Bruder von Musikstar Herbert Grönemeyer ein falscher Ansatz. Die Leistungen im Gesundheitsbereich sollten auch als Wertschöpfung gesehen werden. Dieser Bereich sei zudem weltweit einer mit dem höchsten Wachstum.

Der Vorsitzende der Technologieregion, Karlsruhes Oberbürgermeister Frank Mentrup, sprach von „hochrangigen Projekten", die der Jury die Entscheidung nicht leicht gemacht hätten. Der Ort für die Preisverleihung sei gut gewählt, denn die Firma Biologische Heilmittel Heel in Baden-Baden bekenne sich nicht nur zum Standort, sondern erforsche die Naturmedizin auch mit innovativen Methoden. Heel-Geschäftsführer Ralph Schmidt betonte, dass die Halle, in der der NEO vergeben wurde, die letzte noch freie Fläche des Produktionsgebäudes sei. Auf der Etage darüber werde Traumeel produziert, das wohl bekannteste Arzneimittel aus dem Hause Heel.

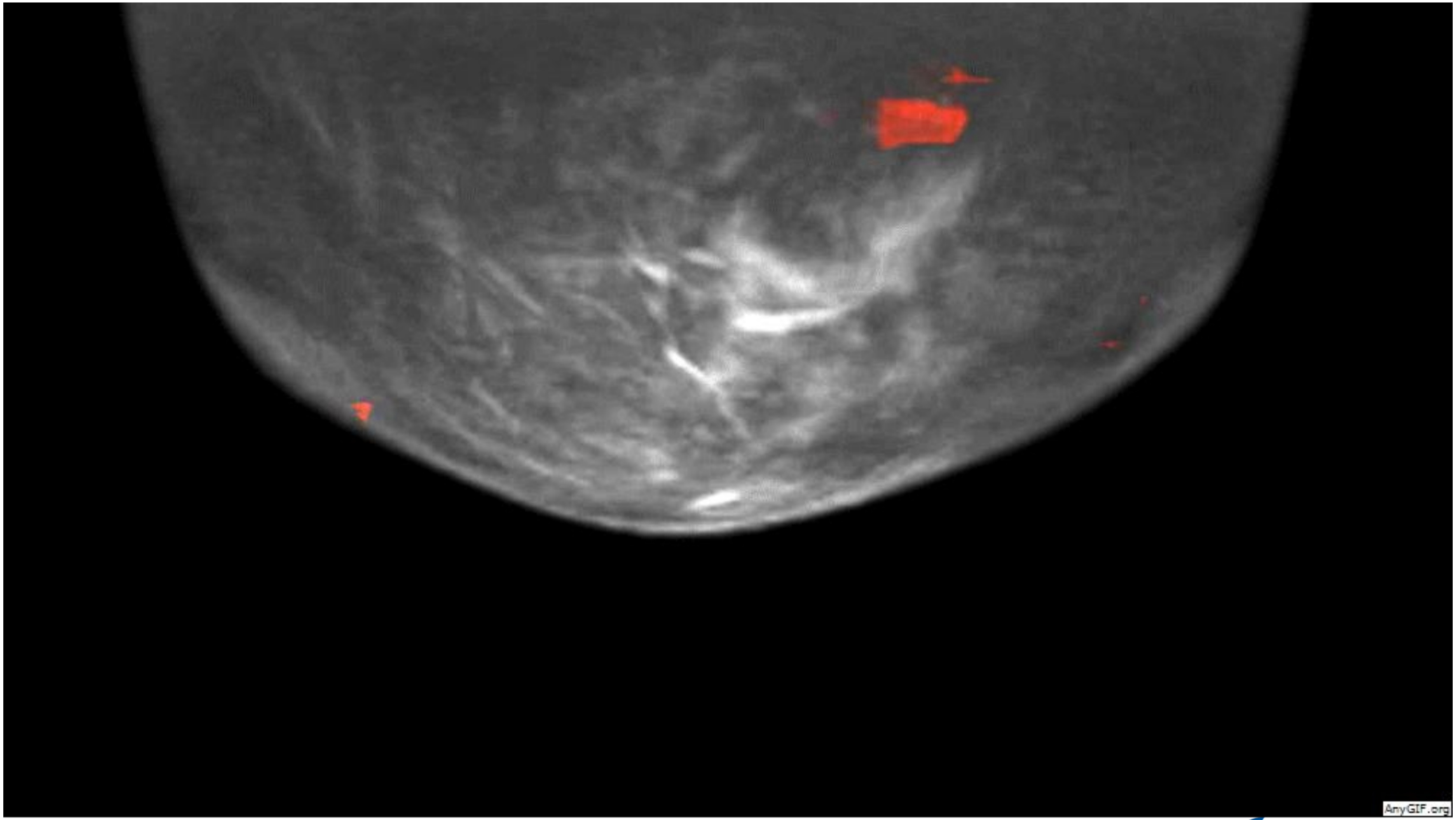
DEUTSCHLANDS BEKANNTESTER ARZT: Dietrich Grönemeyer war Laudator bei der NEO-Preisverleihung in Baden-Baden.

STOLZ AUF IHR TEAM ist Nicole Ruiter. Die gebürtige Rastatterin erhielt gestern Abend aus den Händen von Frank Mentrup (rechts) den mit 20 000 Euro dotierten Innovationspreis NEO der Technologieregion Karlsruhe. Fotos: Fabry

Termin

Dietrich Grönemeyer kommt am 28. November, 20 Uhr, zu einem Vortrag in die evangelische Stadtkirche Karlsruhe. Kartentelefon (07 21) 88 54 68.

First clinical study in university hospital Jena (carcinoma)



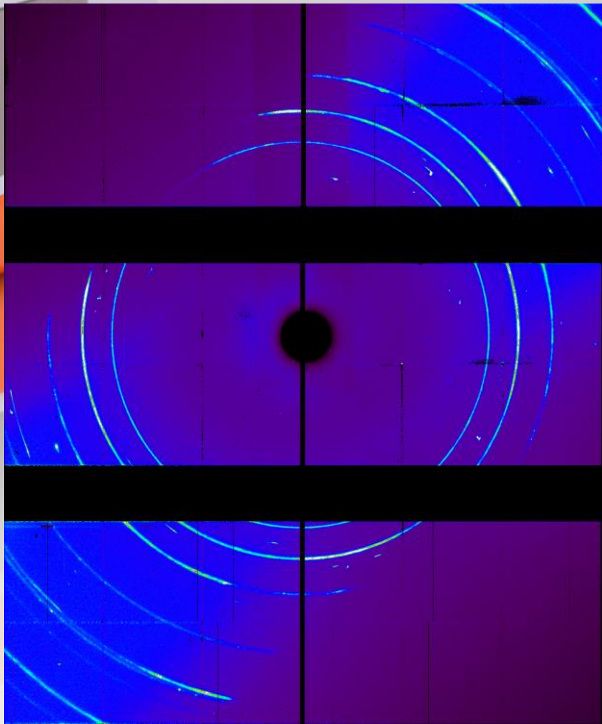
X-Spectrum GmbH founded in 2014 as a spin-off from DESY

Spectrum

LAMBDA

Camera with unique combination of pixel size, frame rate and colour imaging

Diffraction from Bi sample (42 keV X-rays)



Conclusion

- There are many challenges: near-term and long-term
- There are many most promising R&D directions and opportunities
- Future detectors will be so much better than today

Thank you and enjoy the conference!

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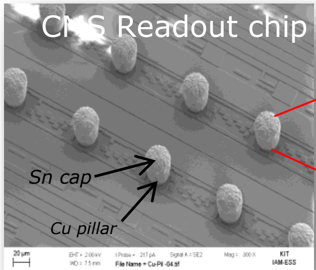
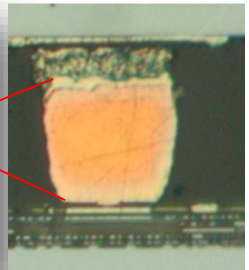
Generic bumping technologies under study

copper pillar



15 µm Cu-pillars on ROC

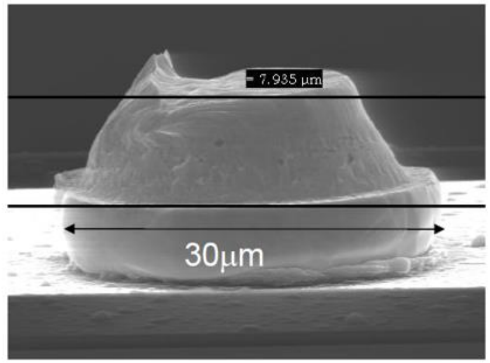


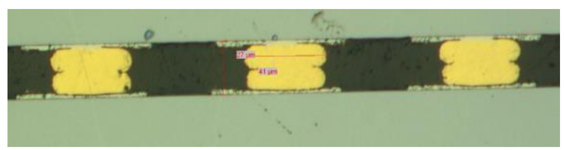
Cross section of Cu-pillar bonded sensor and chip

- Microcontacts on silicon for flip chip interconnects
- Copper Pillars: d=15 µm

gold stud bumping

Bumping Process

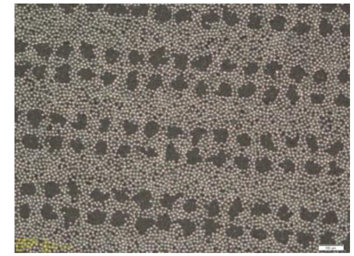




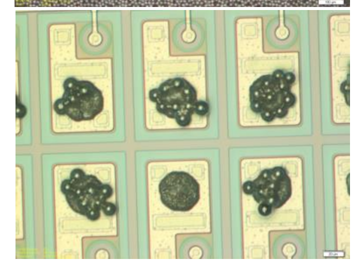
cross section: excellent bonding results

- Bump diameter: ~ 30 µm
- Bump height: ~ 15 µm
- Fast: 18 bumps/s
- High process stability
  → 4000 bumps without one missing

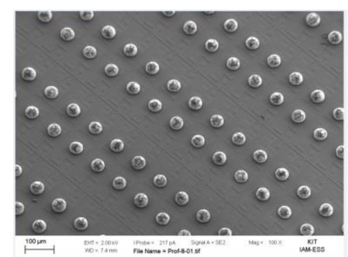
Precoat by powder sheet



PPS sheet after processing



Single sensor with transferred balls



Sensor after reflow

- SAC Bumps with reproducible diameter
- Easy process
- Homogeneous temperature required

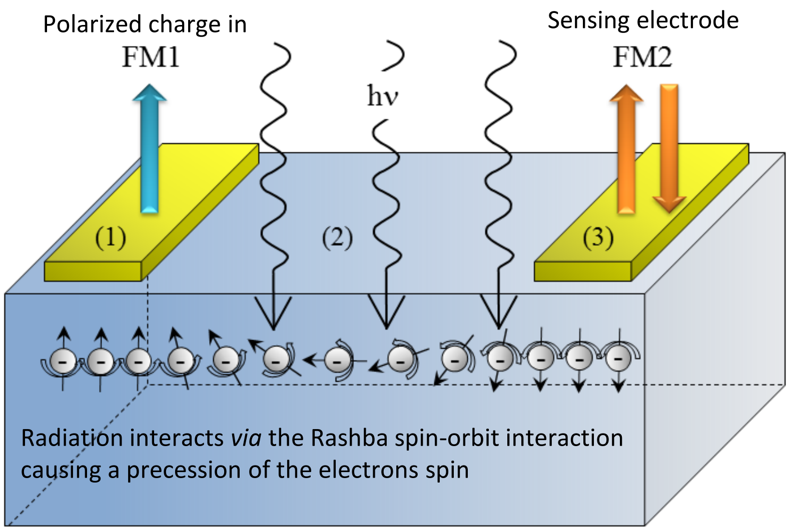
New degrees of freedom

Conventional detection systems only utilize the electrons charge

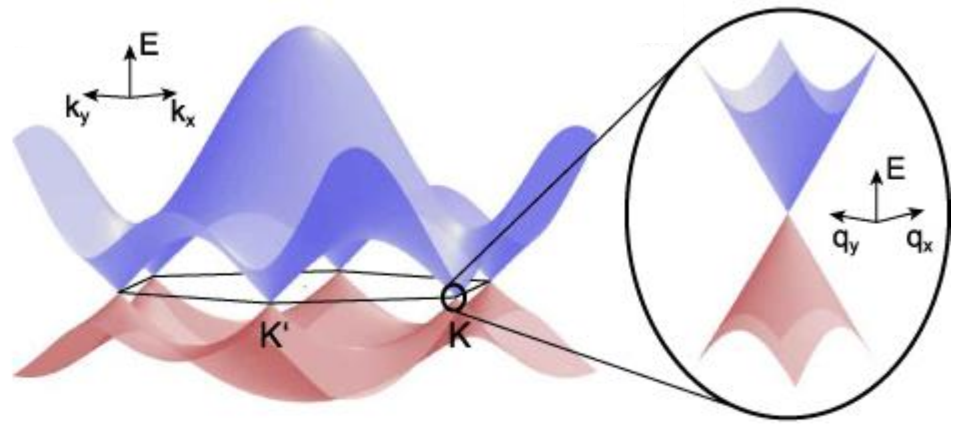
Use the more obscure internal degrees of freedom of the electron, for nonvolatile information processing

Spintronics[1]

The idea is to fabricate device that operates using not just an electron's charge, but also its spin and associated magnetic moment. In an electron, spin behaves like angular momentum, but is not related to any real rotational motion. As a result, the spin of an electron can be switched much more quickly than charge can be moved round. Charge can also be collected in the usual way by applying a potential across the device. . Spin is injected from a polarized source (such as a ferromagnetic metal (*e.g.*, Ni or Fe), FMl) into the active semiconductor region. The polarised electrons then interact with the incident radiation changing the spin of the electrons. The new polarization of the electron is then sensed at the other end of the semiconductor by a second ferromagnetic electrode (FM2)



FM is a ferromagnetic metal such as Ni or Fe



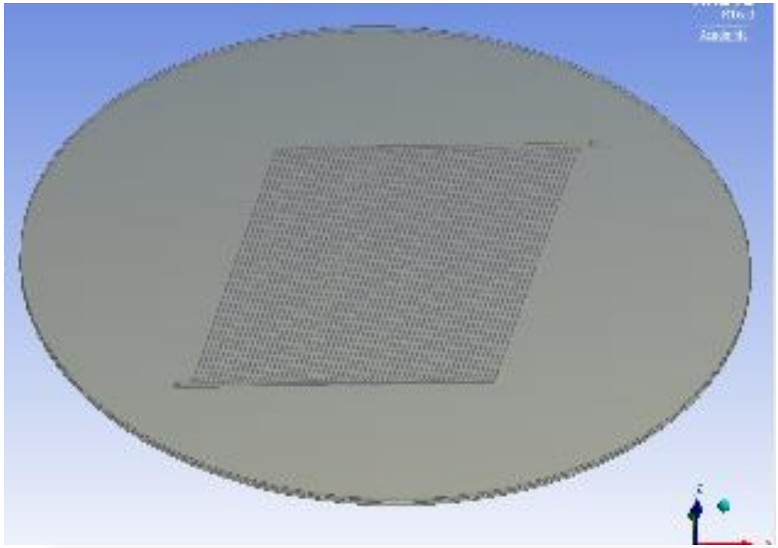
Valleytronics

Like spintronics, valley-based electronics, or valleytronics is another recent development that makes use of the more obscure internal degrees of freedom of the electron, for nonvolatile information processing. It relies on the fact that the conduction bands of some materials have two or more minima at equal energies but at different positions in momentum space. By controlling the number of electrons that occupy a particular valley, it is possible induce a valley "polarization", which can then be used to transmit/process information. This new degree of freedom behaves mathematically in a similar way to the electron spin in that it acts like additional intrinsic angular momentum of the electron. Electrons can be valley polarized by scattering off a line of defects.

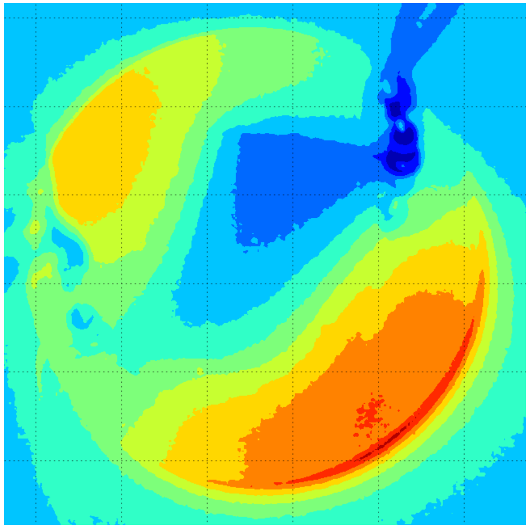
[1]a contraction of "spin transport electronics"

Microchannel cooling

- Microchannels etched into 4” silicon wafer of 500 µm thickness
- Sixty 100 µm x 100 µm channels connected via manifolds
- 675 µm pitch
- Integrated into setup containing flow, pressure and temperature sensors



IR camera picture

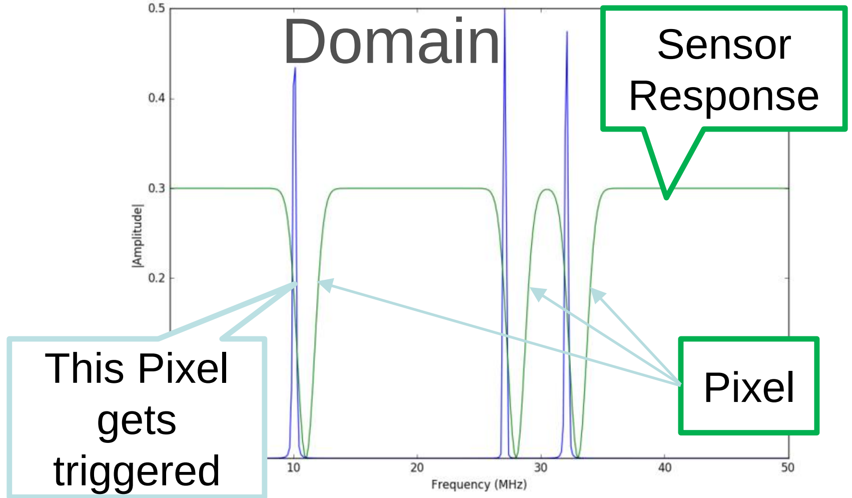


HELMHOLTZ ASSOCIATION

Signal Generation and Modulation

I/Q-Time Domain

Frequency Domain



Frequency Mixture

Amplitude Modulation

Frequency Mixture Modulated