Development of Silicon Detectors for Particle and Astroparticle Physics Experiments

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der Max-Planck-
Institute
für Physik und
extraterrestrische
Physik

MPI Halbleiterlabor

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Munich
13.12.2004

Complete design and manufacturing chain

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- Facilities for Layout and Simulation of Semiconductor Devices
- Production of Silicon Detectors
- Mounting and Tests

- Special Features:

- Processing of ultra-pure silicon wafers (10^{12} impurites/cm^3)
- Double sided wafer processing
- Wafer scale detectors (up to 50 cm^2 area)

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Range of Devices

Device	Project (WHI, MPE)
Silicon Strip Detectors, passive Pixel Detectors design and prototyping production in industry quality control	ATLAS
pn-CCD for imaging X-Ray (and optical) detection frame store CCDs	XMM/Newton ROSITA/DUO CAST
Silicon-Drift-Detectors X-ray spectrometers many design derivatives: arrays integrated amplification (DEPFET) gated diodes	Siddharta DRAGO FELIX Muon Cooling
Active Pixel Detectors (DEPFET) for X-ray imaging and tracking detectors	XEUS ILC (TESLA)
Silicon Photomultipliers (R&D project) single photon detection	MAGIC, EUSO

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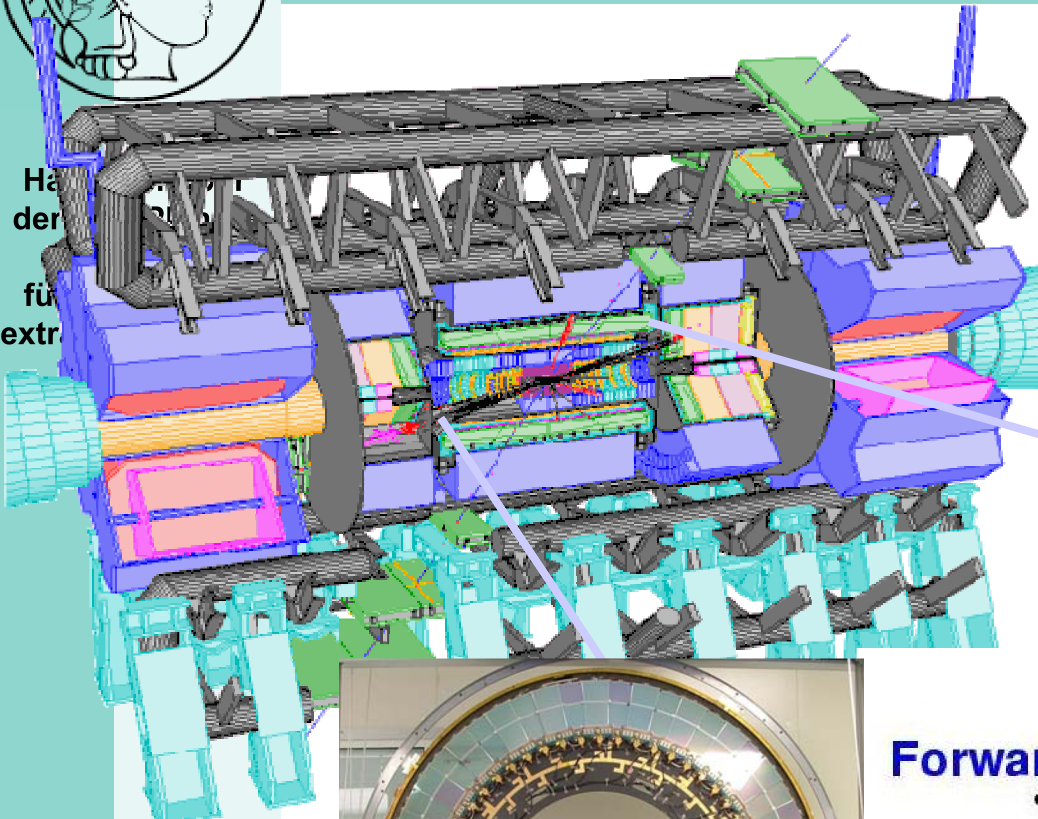
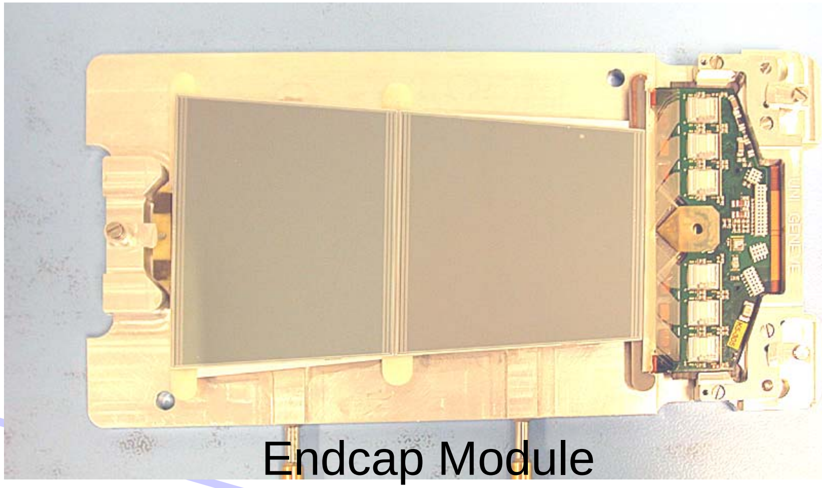
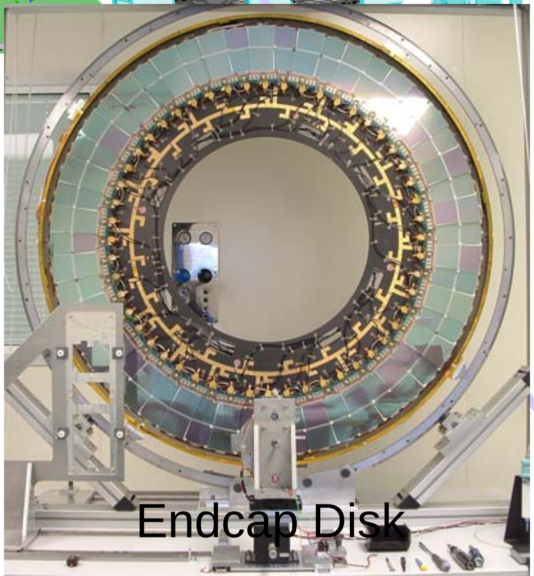
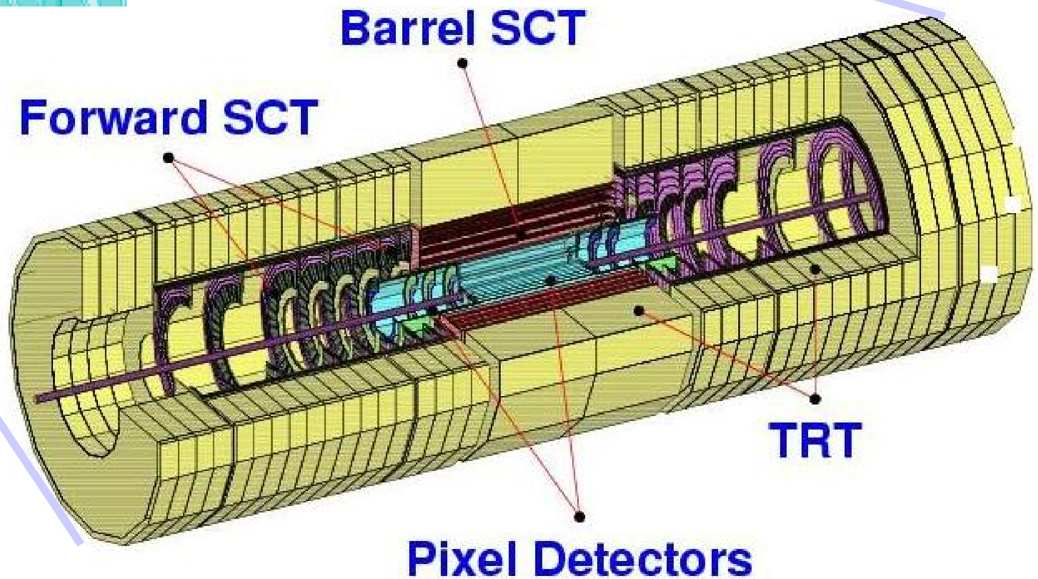
Silicon Strip Detectors for ATLAS SCT









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Silicon Stripdetector: ATLAS SCT

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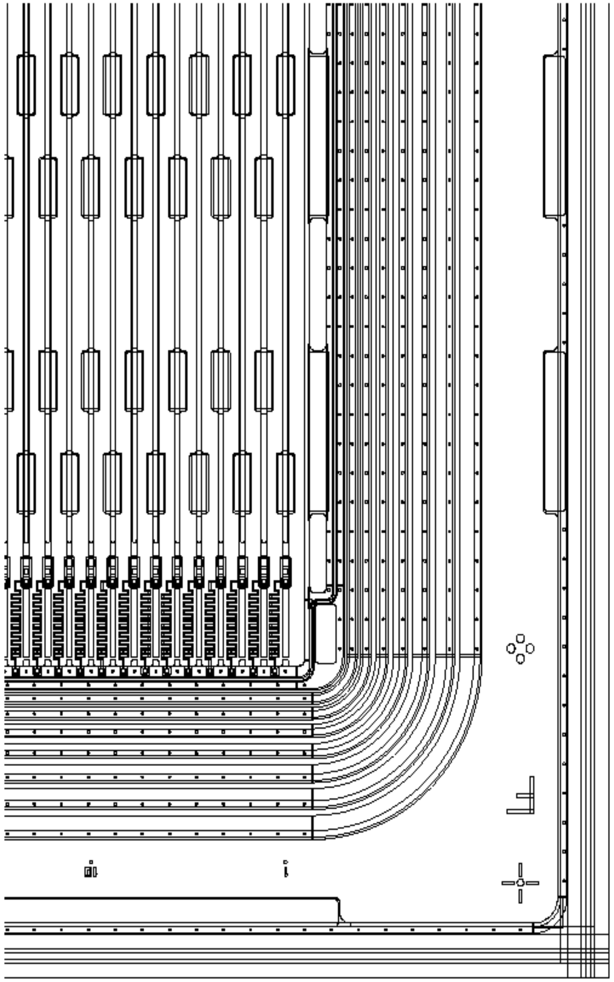
- Radiation tolerant up to $3x10^{14}$ p/cm^2
- p-on-n single sided detectors
- 285 micron 2-8 kOhm
- 4“ substrate
- Barrel: 64x64 mm^2
- Forward: wedge shaped (5 shapes)
- 768 readout strips with ca 80 μm pitch
- No intermediate strips
- AC coupled strips
- Polysilicon or implanted bias resistors
- Multiguardring structure to ensure stability up to 500 V
- Ca. 20000 needed
- 3100 produced CIS

competed, however, some problems with properties of passivation layers:



High resisitivity of passivation layer leads to:

Early breakdown (<450V) if operated in N2 atmosphere (10%-20% of detectors affected)

Noise bumps due to strips shorted by surface charges
Cured by treatment with ionized air

Future: detectors for Super-LHC ???

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Silicon Drift Detectors

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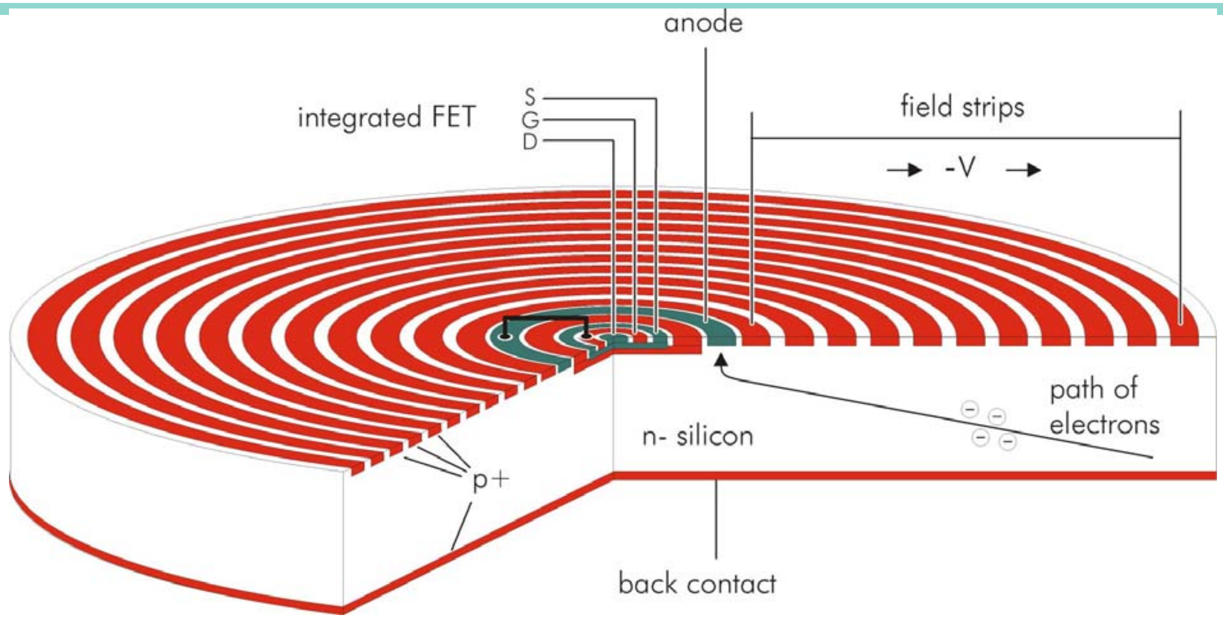

Large detection area
Low capacitance => Low noise
Integrated Transistor for first amplification
Can be produced in many shapes
Many other detectors based on this principle

Projects: SIDDHARTA (Kaonic Atoms); Muon Cooling

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Example: Mars Rover

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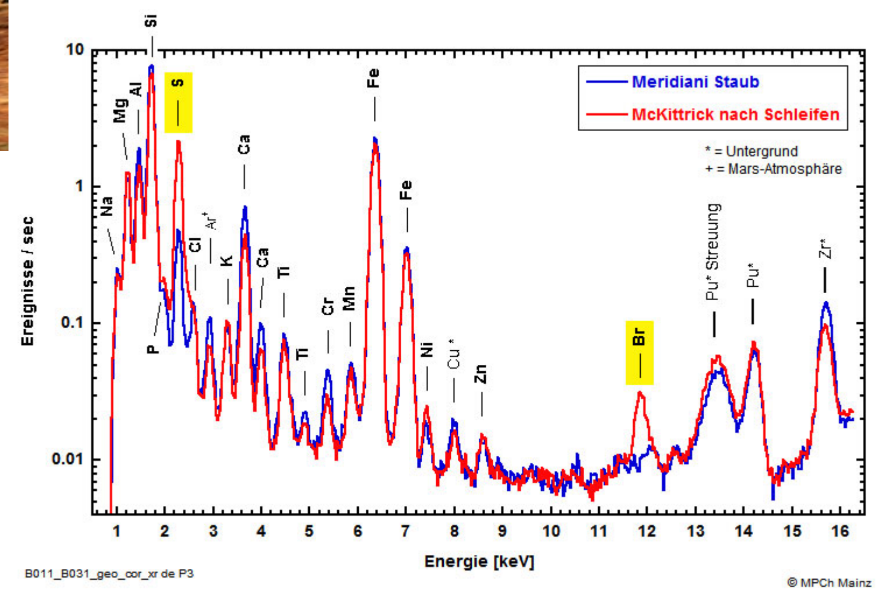
Silicon Drift Detectors for

APXS X-ray flourescence spectrometer for MPI fur Kosmochemie, Mainz

mission profile

- 2 independent mobile landers
  “Spirit” & “Opportunity”
- arrived 04./25.01.04



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Muon Collider: Frictional Cooling Experiment

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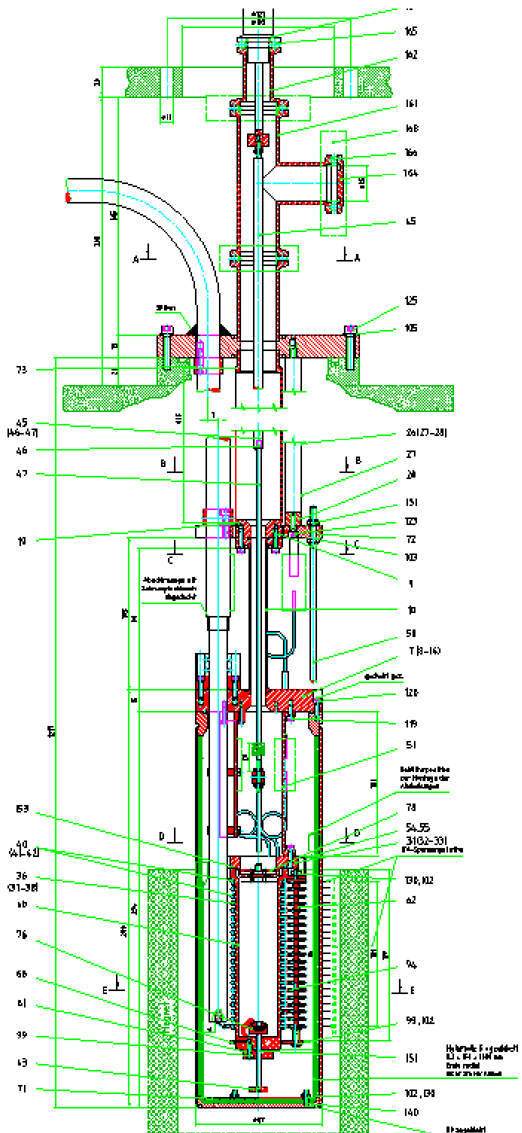
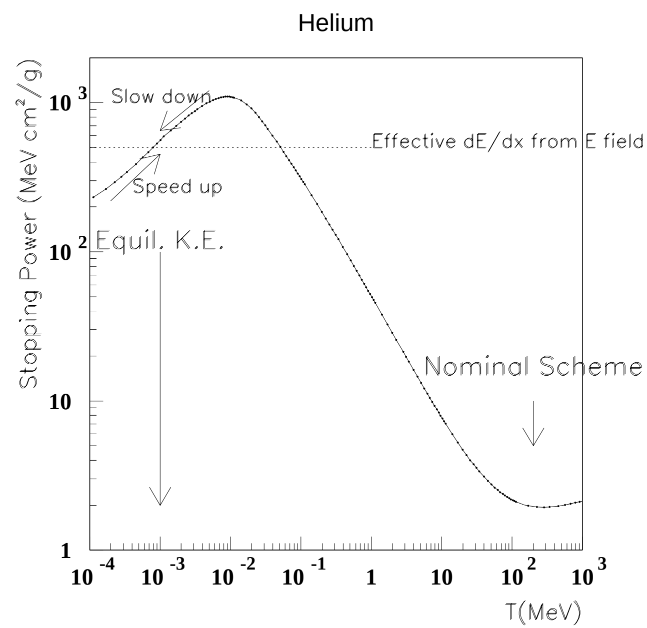


Muon Collider:

- **No synchrotron problem – better than electron**
- **Point particle – better than proton**
- **But, τ=2.2 10^{-6} s, so**
- **need μ production, cooling, acceleration, within very short time !! We focus on cooling.**



$\mu^- + He \rightarrow He_\mu + e + \gamma$'s

Transition n=2$\rightarrow$n=1 releases few KeV x-ray

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Gated Drift Diode

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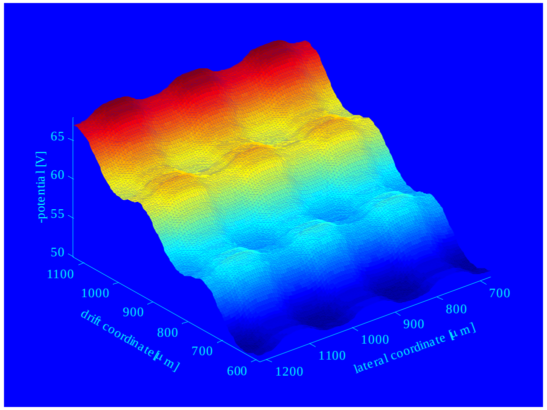
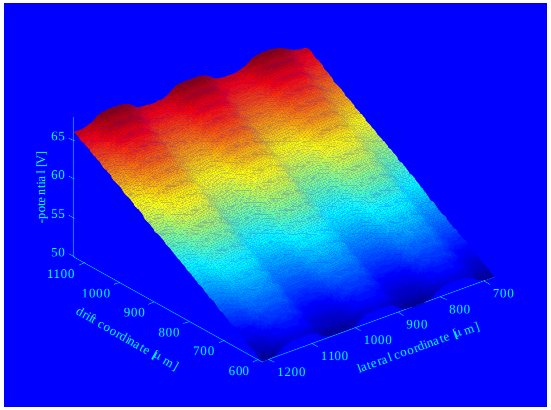
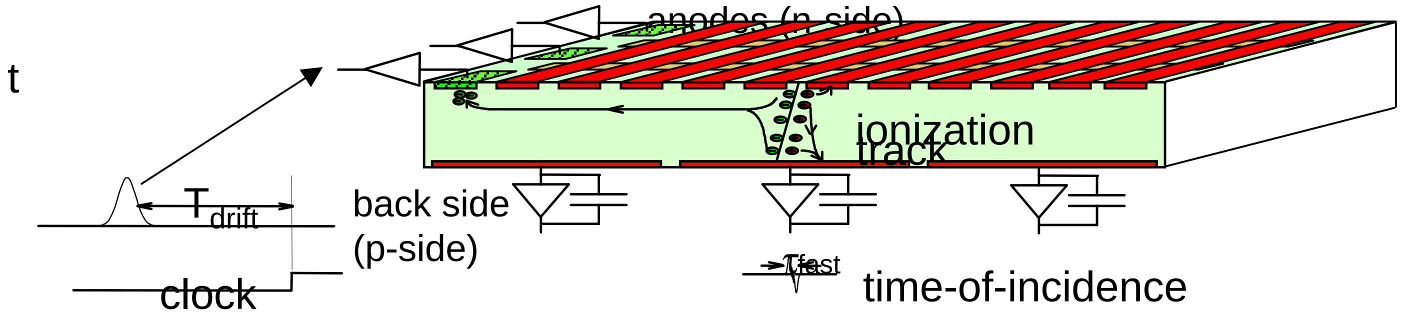
In drift diodes: t_0 infomation is missing: no spatial resolution.
Modulation of drift fields allows to store charge temporarily.
Drift starts if potential walls are removed.
Back side contacts can serve as trigger.

Application: Medical Imaging (DRAGO, in production)







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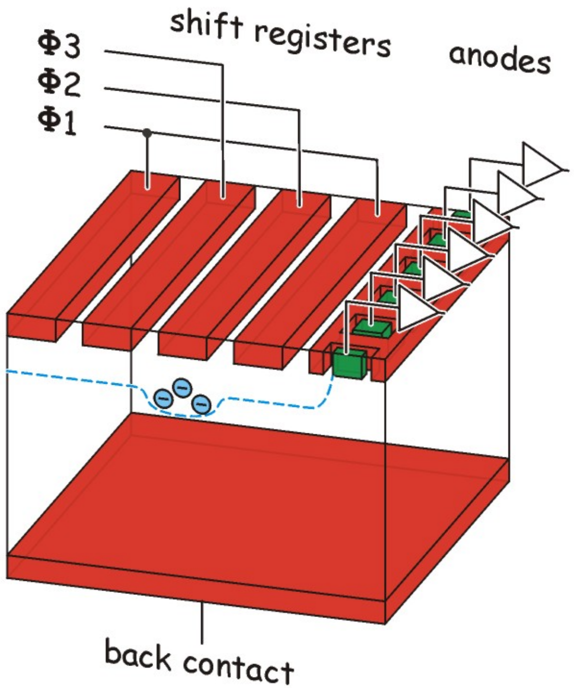
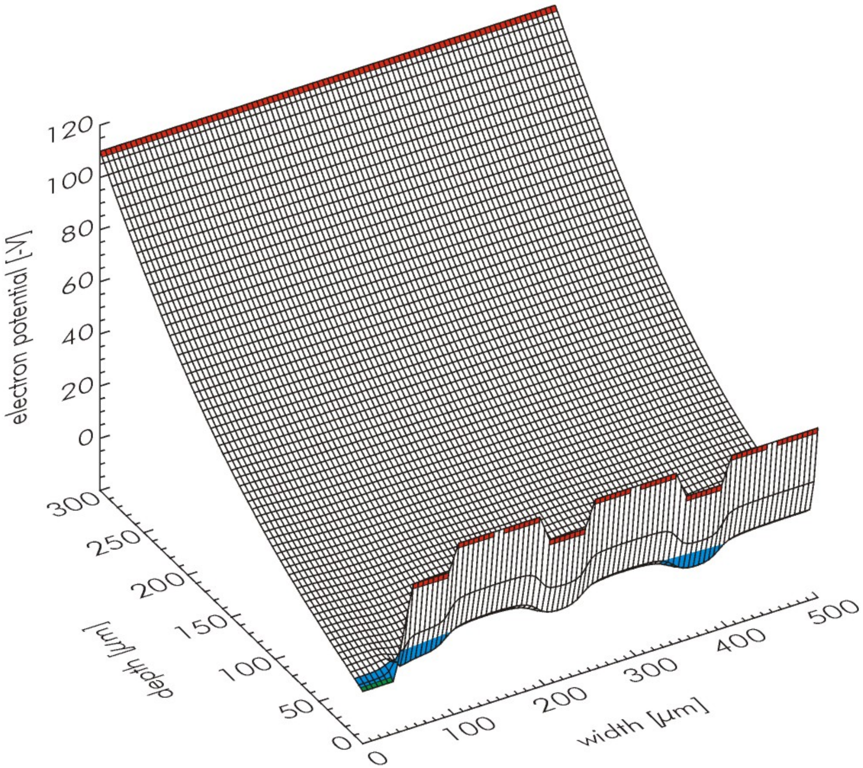
Pn-CCDs





Like in CMOS CCDs (digital cameras) the charge is stored between potential walls and shifted by periodically modifying them

Unlike in CMOS CCDs the complete bulk is depleted and the CCD is sensitive to X-rays

Disadvantage: out of time events

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Application in XMM/Newton

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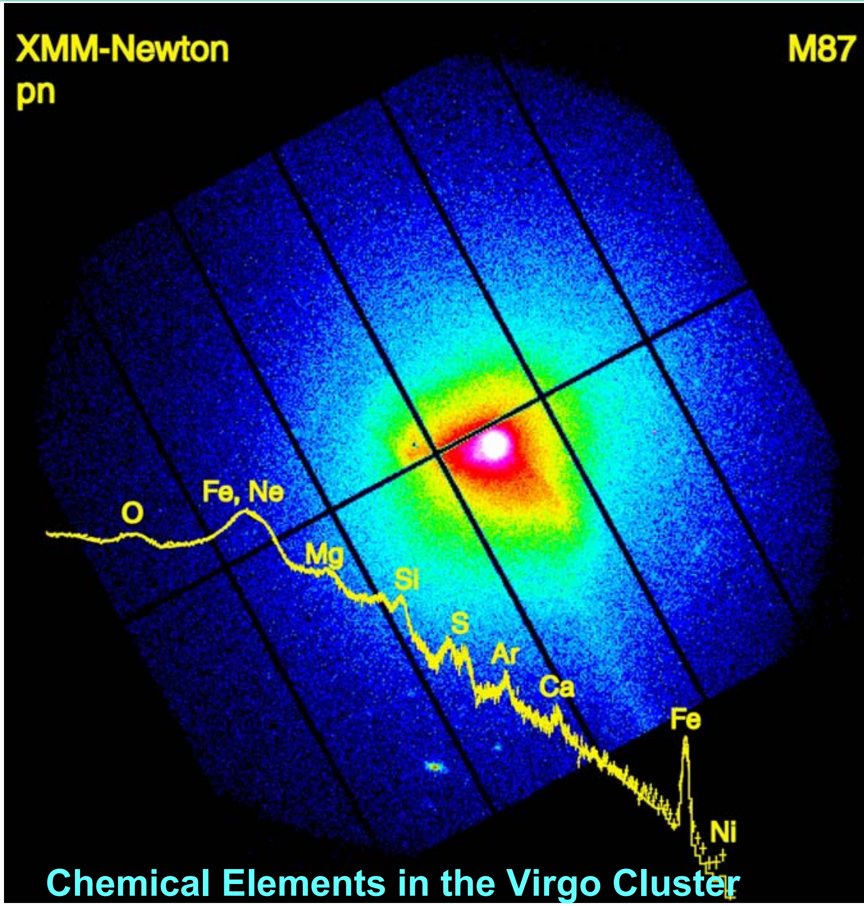
Astronomy:

X-ray CCDs (XMM-Newton):
in orbit since Dec 1999
taking data
operation support and surveillance

World's largest X-ray CCD
Flawless operation since 5 years



Chemical Elements in the Virgo Cluster

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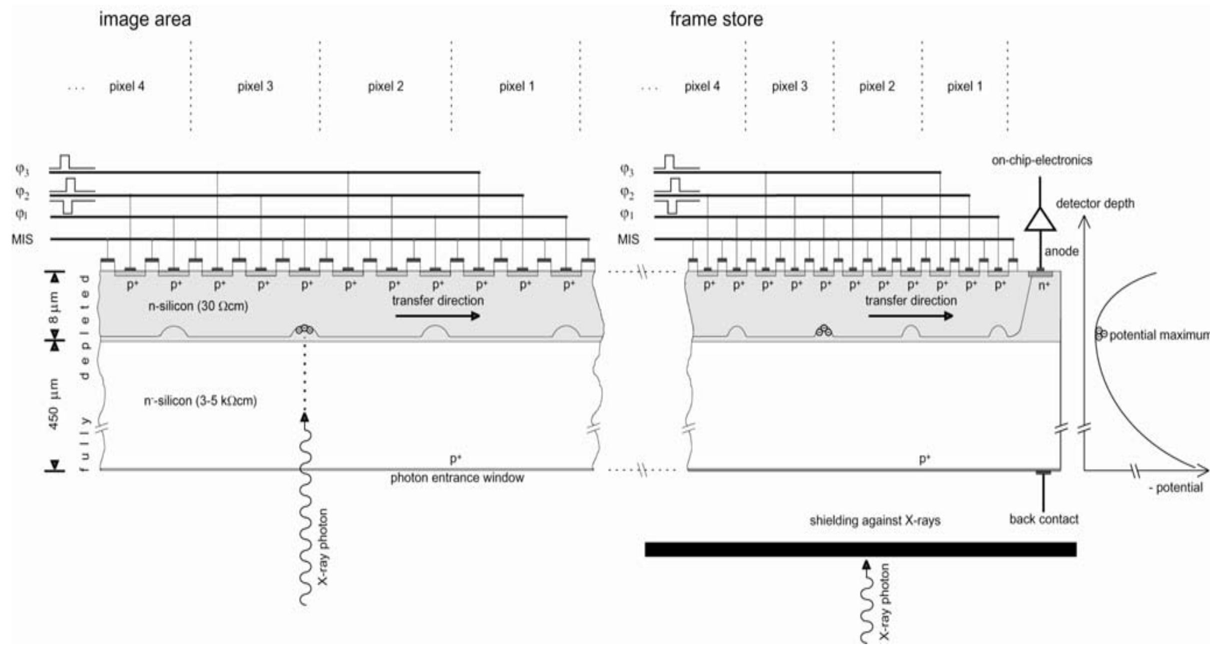
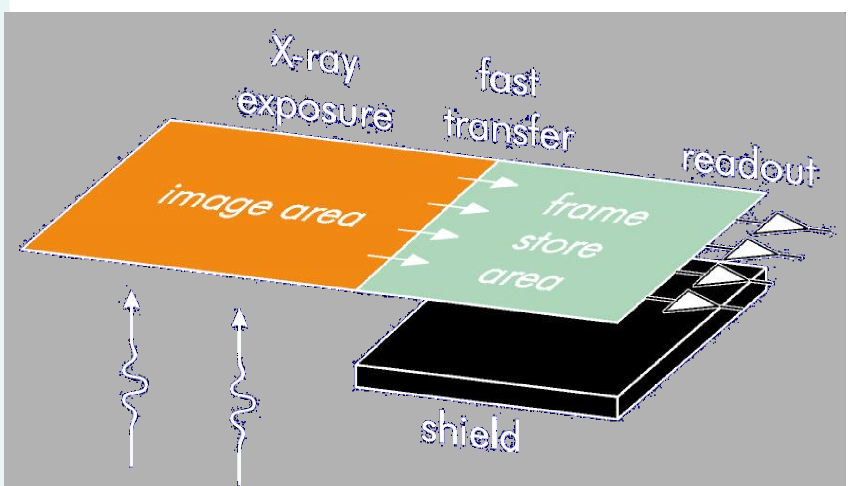
Frame store PN-CCD (DUO/ROSITA)

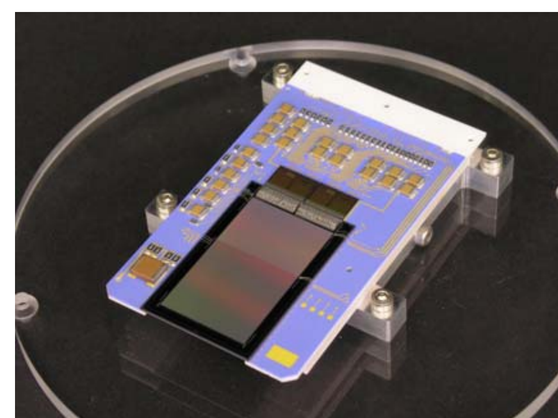
Fast transfer in shielded storage area for readout

DUO flight model detectors produced

DUO mission scheduled for 2007







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DEPFET Pixel Detectors

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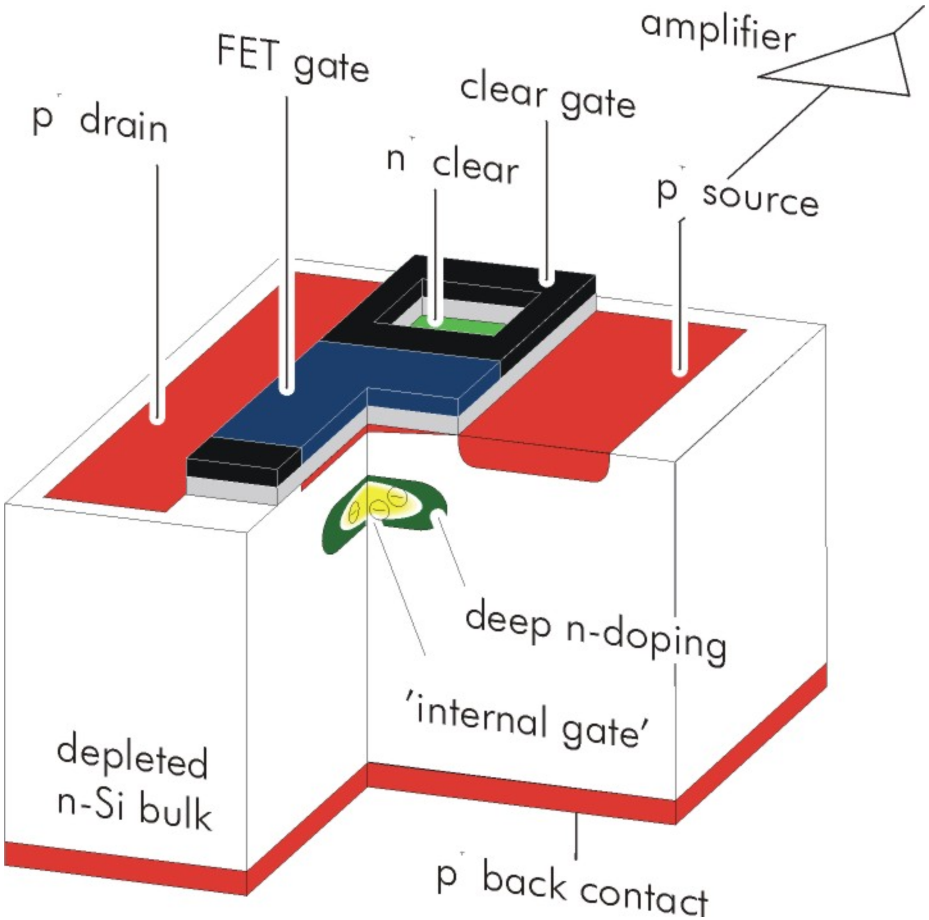
DEPFET: MOSFET Transistor on depleted silicon bulk
Complete charge collection and storage
Current readout
Random access of pixels
Fast readout
Low power consumption

Scalable design:
Variable pixel size for applications in spectroscopy and tracking



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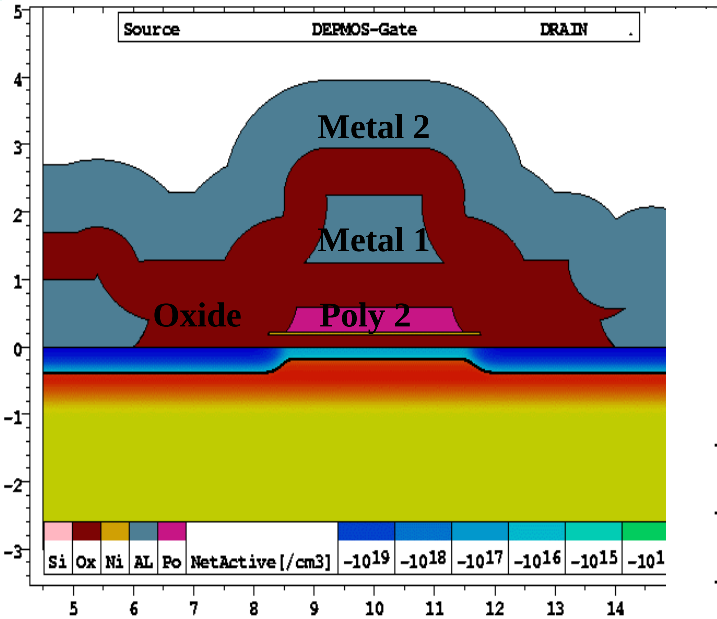
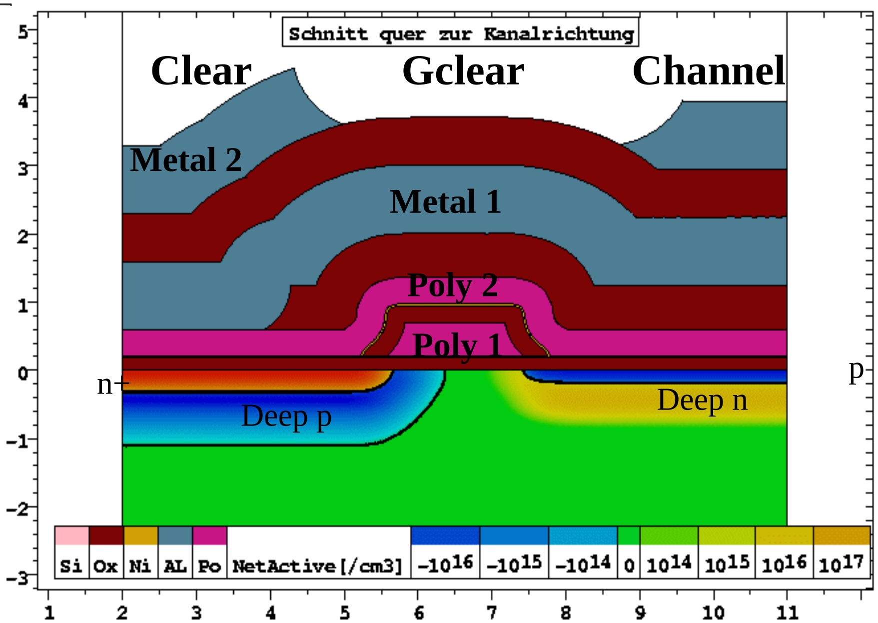
DEPMOS Technology

Double poly / double aluminum process
on high ohmic 150mm wafer



Along the channel



Perpendicular to the channel
(Clear region)

Double metal necessary for matrix operation
Self-aligned implantations with respect to polysilicon electrodes => reproducible potential distributions over large matrix areas
Low leakage current level: < 200pA/cm² (fully depleted – 450µm)

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DEPFET Operation: Energy Resolution

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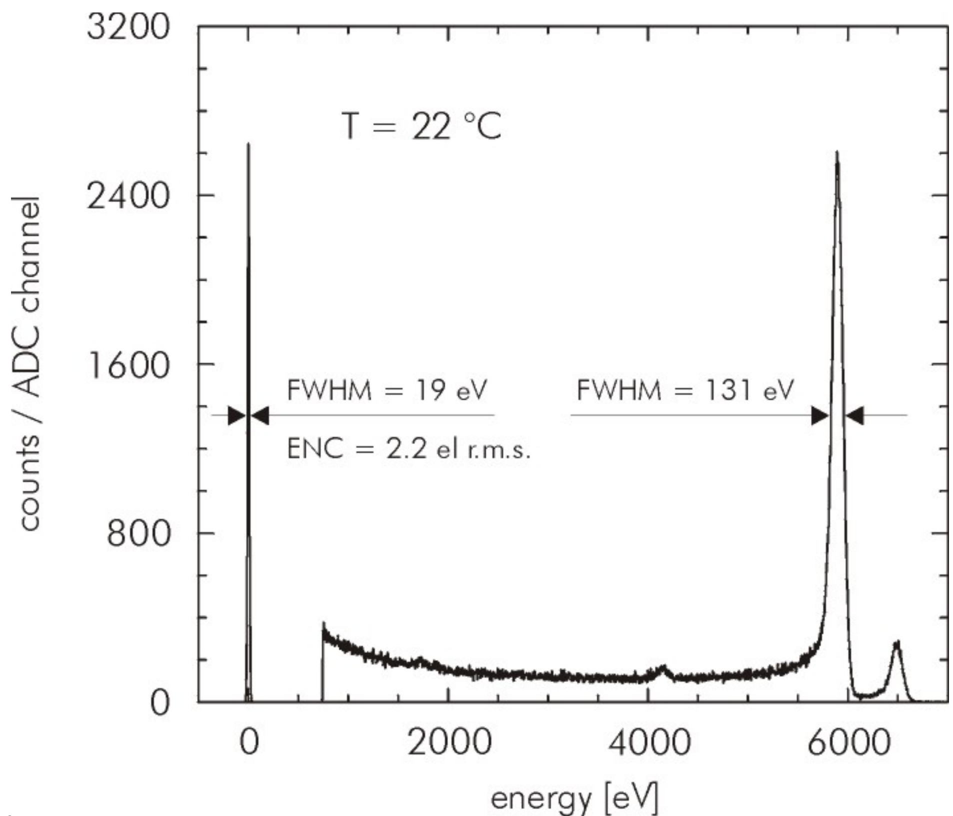
Excellent energy resolution already at room temperature

(measured with a single DEPFET)



Setup:

- source follower read out
- commercial pre-amp
- shaping time 6 µs

"best case conditions"

Best result at Room Temperature:

- **131 eV @ 5.9 keV**
- **2.2 el. r.m.s.**

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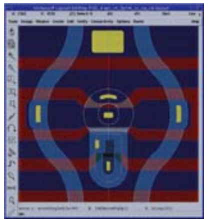
Many Design Variations and Applications

Mini-Pixel
Rectangular DEPFET structure:

D1 D2
Gate 1
Gate 2

High position resolution
ILC cell size: 25x25µm²
Double readout speed by
Parallel readout

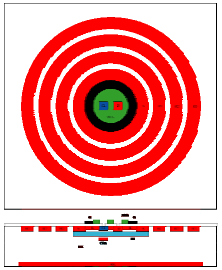
Midi-Pixel
Circular DEPFET structure

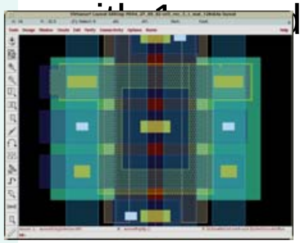


High energy resolution,
medium position resolution

XEUS wide field imager
cell size: 100x100µm²

Maxi-Pixel
Integration of a DEPFET
into a drift detector
drift rings





High energy resolution,
coarse position resolution

SIMBOL-X, ECLAIR
cell size: ~ cm²

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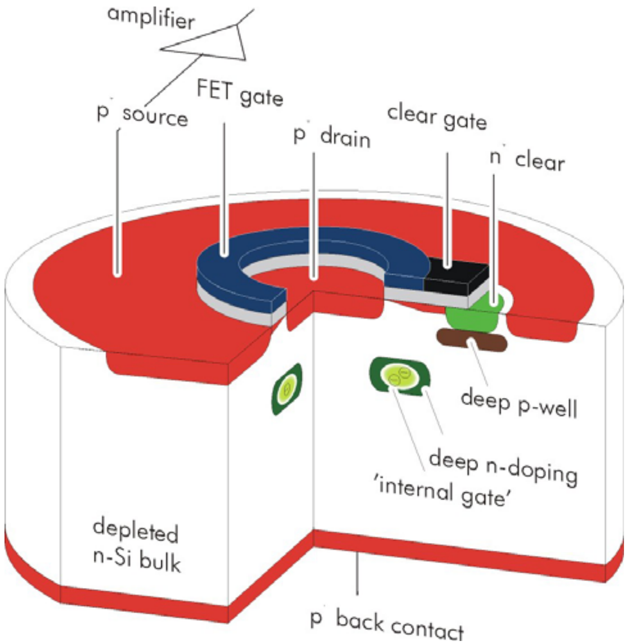
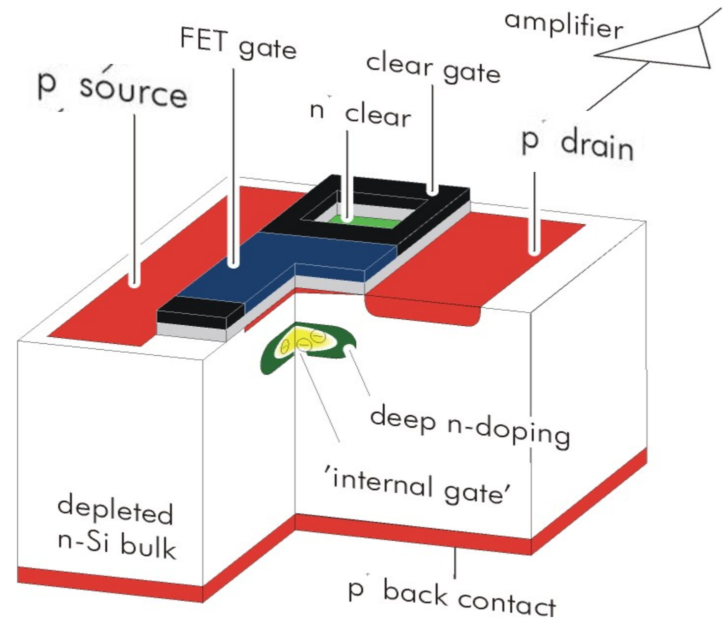
PXD4 - DEPFET: Two projects on one wafer





	XEUS (N14-6)	*ILC*
purpose	imaging spectroscopy	particle tracking
sensor size	7.68 x 7.68 cm²	1.3 x 10 cm², 2.2 x 12.5 cm²
pixel size	75 µm	25 µm
sensor thickness	300 ... 500 µm	50 µm
noise	4 el. ENC	~ 100 el. ENC
Readout time per row	2.5 µs	20 ns

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Application: XEUS WFI

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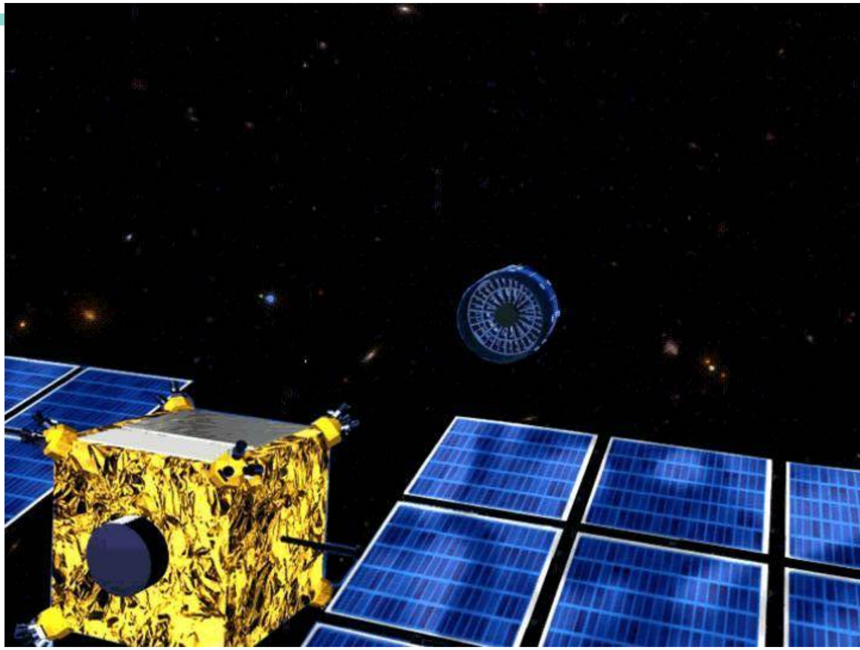
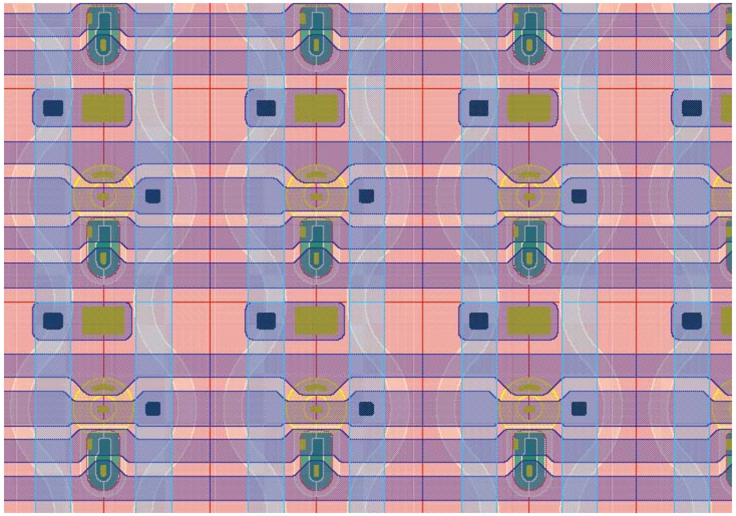
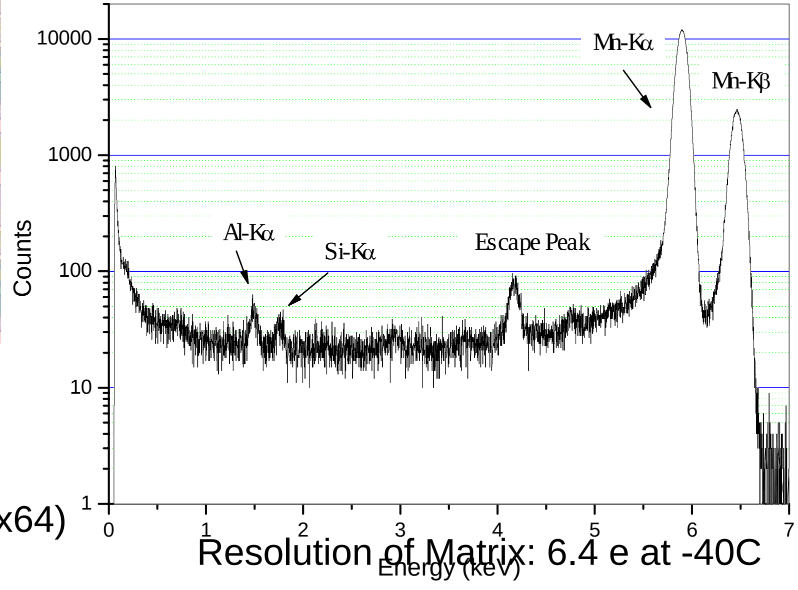
Mission concept:

- X-ray telescope consisting of two satelites, mirror (MSC) and detector (DSC) spacecraft
- Formation flight; active control of focal length with 1 mm³ accuracy





Prototype Matrix with 75µm x 75 µm pixels (64x64)



Resolution of Matrix: 6.4 e at -40C

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Vertex Detector for TESLA

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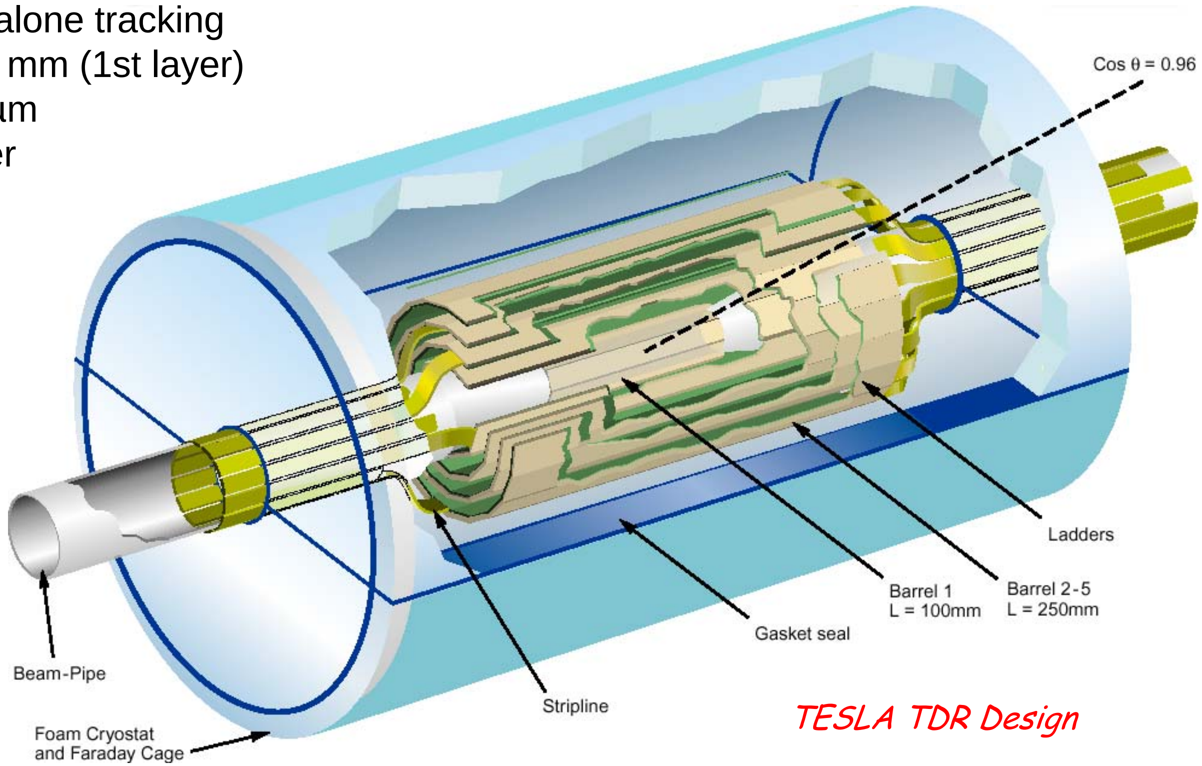
sensitive area 1st layer module: 100x13 mm², 2nd-5th layer : 125x22 mm² ➔ ∑120 modules

TESLA TDR:

- 5 barrels – stand alone tracking
- close to IP, r = 15 mm (1st layer)
- pixel size: 20-30 µm
- ~0.1% X_0 per layer
- overall: ~ 1GPixel



TESLA TDR Design

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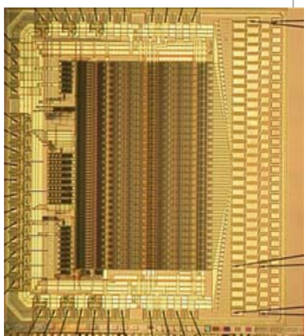
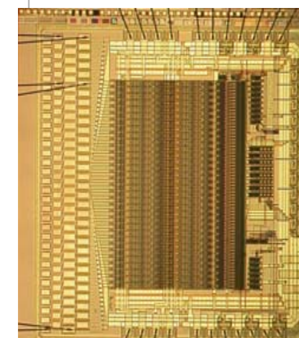
DEPFET Matrix Operation

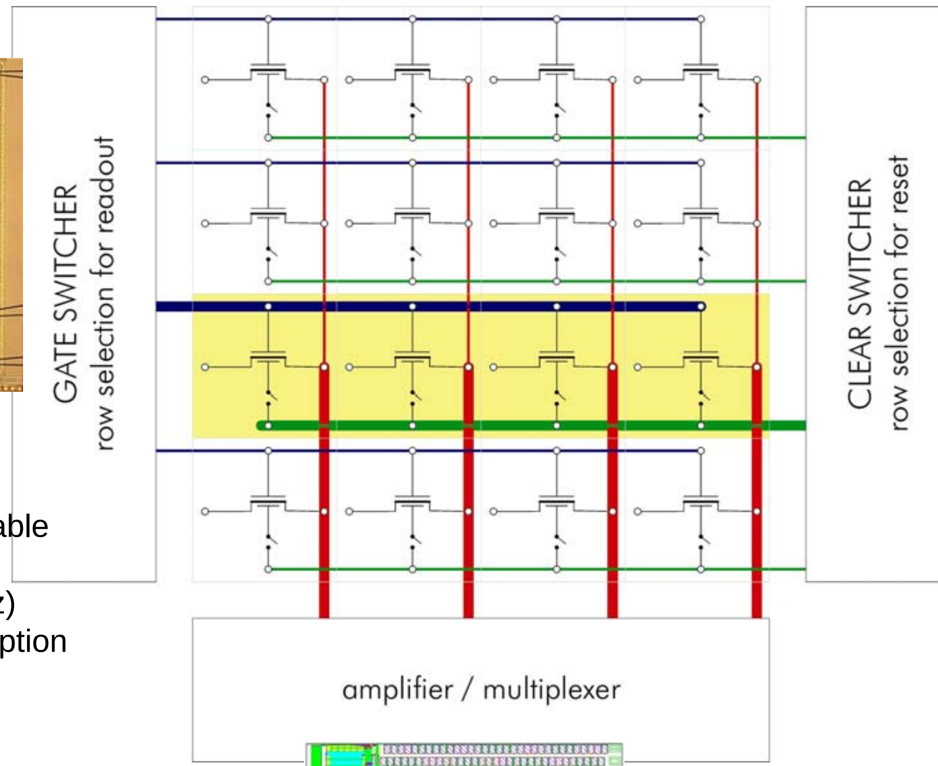
ASICs developed by Universities Bonn and Mannheim

Switcher II



Switcher II





64 channels, chainable
20V voltage range
High speed (30MHz)
Low power consumption
(1 mW/ch)

128 channels Current readout
Correlated double sampling
(before/after cear: pedestal
suppression)
Hit identification, 0-suppression

Test setup exits and working
Testbeam scheduled January 2005

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Test with Sr90 Source

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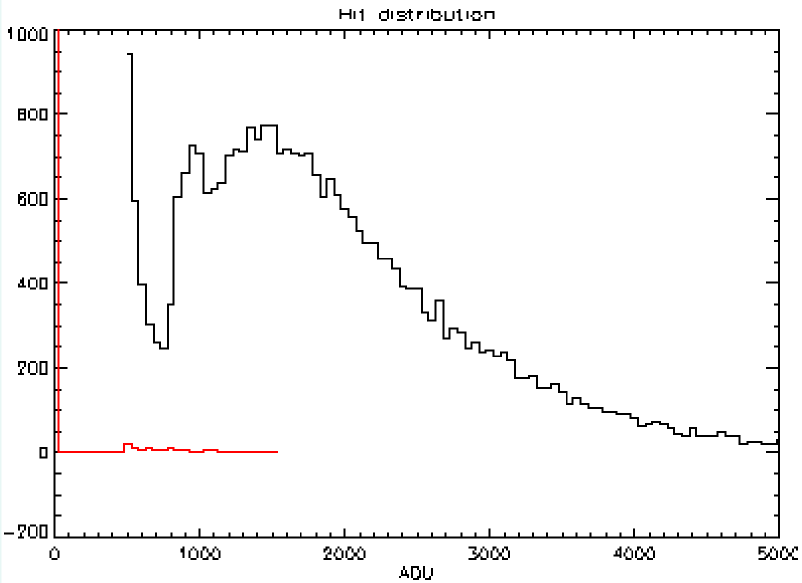
First results with source test (Sr90):

**Noise ~80 ADC counts
(not yet optimized, 30 achieved with different amplifier)**

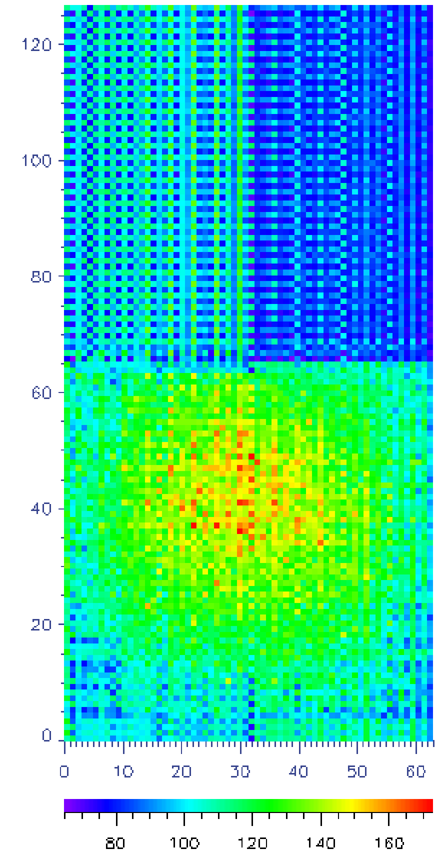
Most likely signal size: 1500 counts

**Noise still dominated by hybrid layout problems.
Ok for testbeam (January)**



Hitmap

Region without detector
Region with DEPFET



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ILC Vertex Detector: Module Concept & Material Budget

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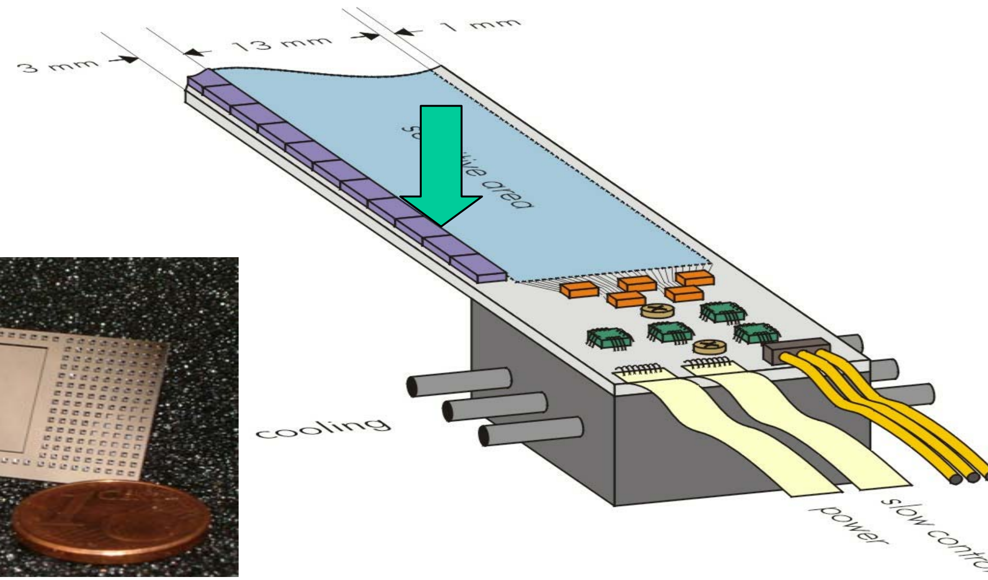
Sensitive area thinned to 50 μm, supported by 300 μm Si-frame



Estimated Material Budget (1st layer):

Pixel area:	100x13 mm^2, 50 µm	0.05% X_0
steer. chips:	100x2 mm^2, 50 µm	0.008% X_0
(massive) Frame :	100x4 mm^2, 300 µm	0.09% X_0

perforated frame: 0.05 % X_0

total: 0.11 % X_0

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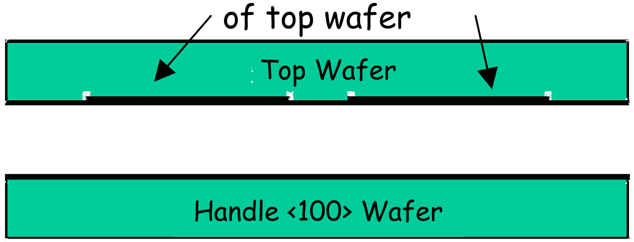
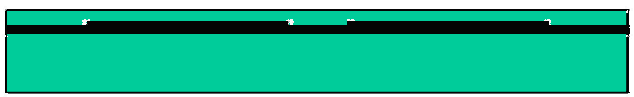
Processing thin detectors

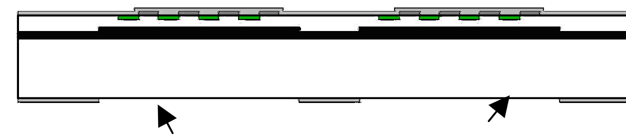
a) oxidation and back side implant of top wafer



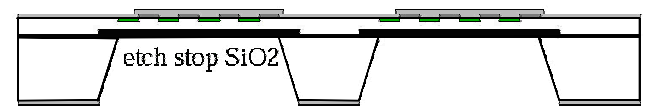


b) wafer bonding and grinding/polishing of top wafer

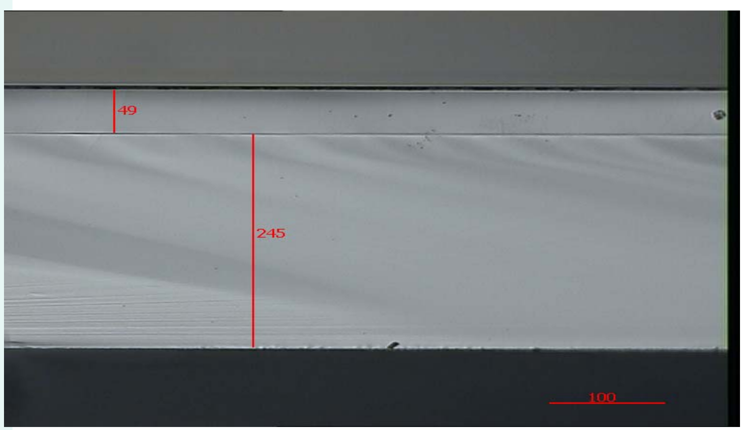
c) process ➔ passivation

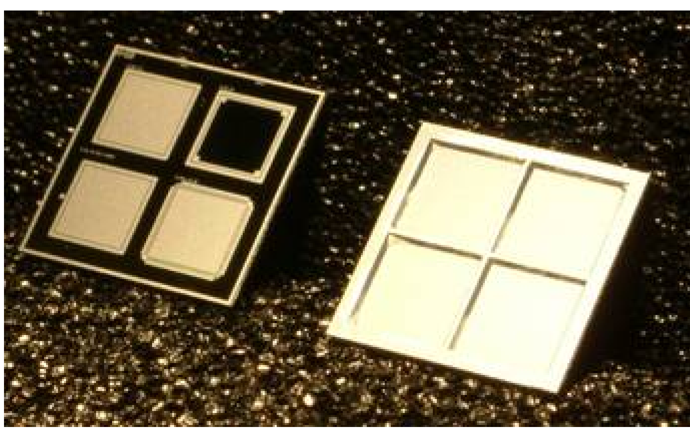


open backside passivation



d) anisotropic deep etching opens "windows" in handle wafer





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PiN Diodes on thin Silicon

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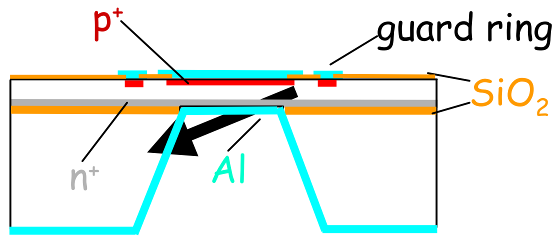
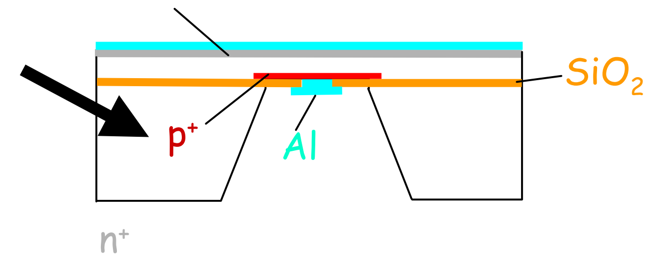
Type I: Simplified standard technology



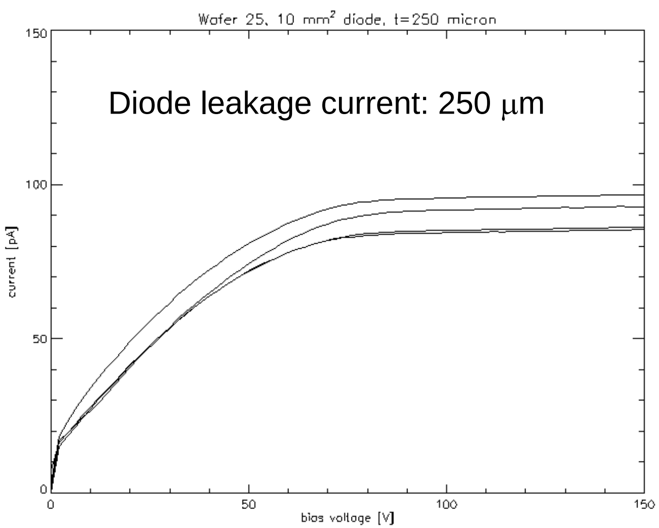
structured p+ on top
unstructured n+ in bond region
10 mm² diodes

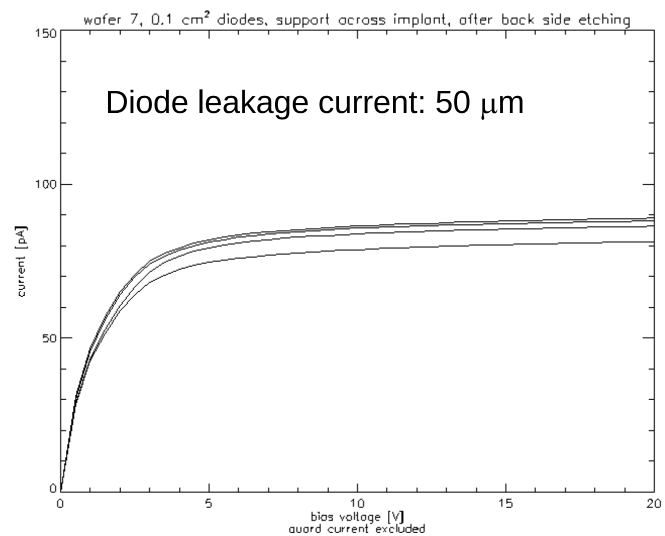
Type II: Implants like DEPFET config.



unstructured n+ on top
structured p+ in bond region
0.09 cm² .. 6.5 cm² diodes

- Wafer Bonding: MPI for Microstructure Physics, Halle, (U. Gösele, M. Reiche)
- Top Wafer grinding and polishing: Sico Wafer GmbH, Jena
- Processing and deep etching: HLL





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DEPFET & Competitiors for ILC

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	Resolution 5(+)10/p $\sin^{3/2}\theta$ µm	Material budget $\leq 0.1\%\ X_0/l$.	Read out Speed (50 MHz)	Power consumpt.	Radiation tolerance Ionisation, n	Remarks
CCD	4.2(+)4.0/p $\sin^{3/2}\theta$ µm + +	+ R&D	O? R&D !!	?	+? R&D	Like in SLD
HAPS Hybrid APS	7µm -	- -	+ +	- -	+ +	Like in ATLAS
MAPS Monolithic APS CMOS Microelectr.	2µm +++ But at 50MHz ?	+ R&D	? R&D !!	+ ?	+? R&D	
DEPFET	Like CCD + +	+ R&D	+? R&D	+ +	+? R&D	

Advantages of DEPFET Arrays at ILC

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1. Charge generation and first amplification in a fully depleted pixel cell:
   → good Signal/Noise

2. No charge transfer needed:
   → better rad. hardness for hadronic irradiation
   → fast read out

3. Wafer scale arrays possible, no stiching of reticles(chips) needed:
   → easier module construction, less material

4. Only one row at a time active, read out at the ladder end:
   → low power consumption, less material

5. Radiation Hardness ??
   → to be demonstrated

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Radiation Hardness

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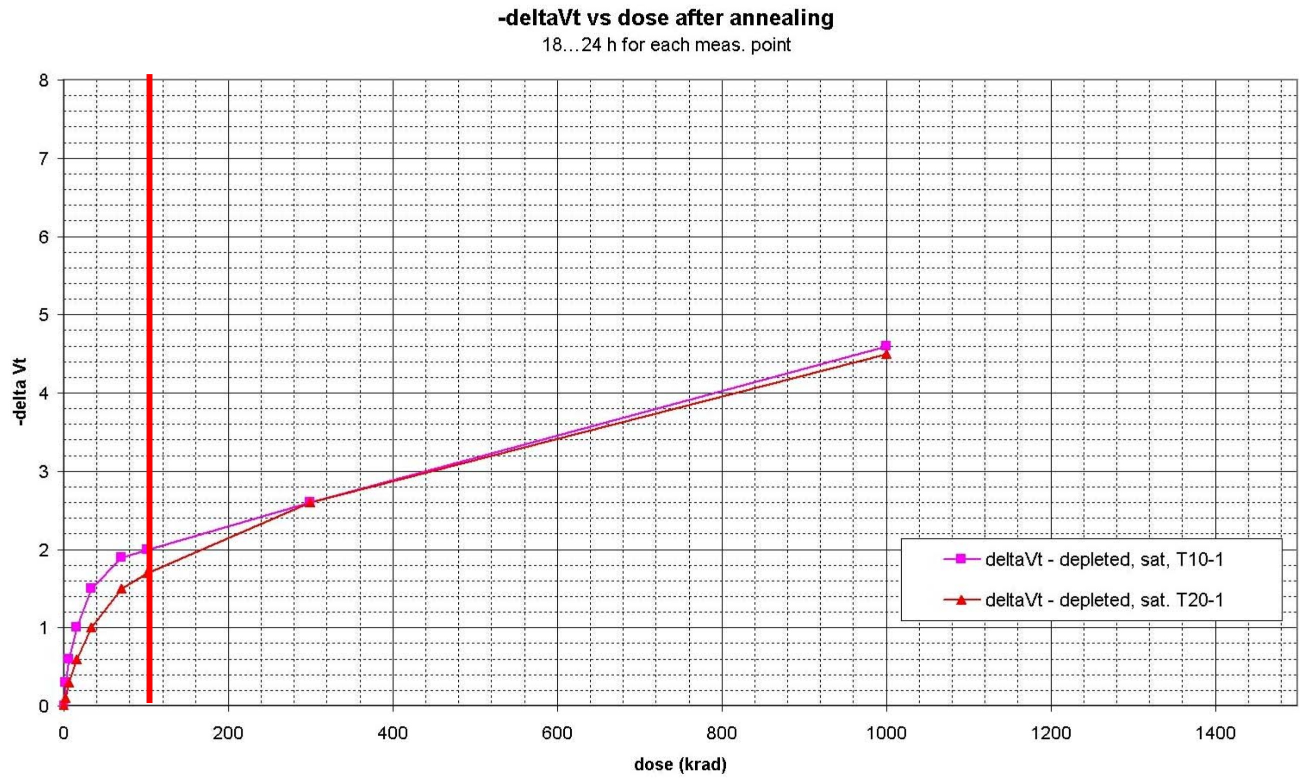

Gate voltage shift after irradiation
ILC expectation: 100krad in 5 years
~ 2V shift: to be compared to ~20V gate/clear voltage: looks promising!

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Development of Silicon Photomultipliers

Photon Detectors developed at HLL so far:

- Single X-ray detection: many electrons/photon
- Measure energy, position and time of arrival
- For optical photons only flux measurements are possible

New experiments require single optical photon detection
with high quantum efficiency:

- EUSO (Extreme Universe Space Observatory)
- MAGIC (Major Atmospheric Gamma Imaging Cherenkov Telescope)
- High Time Resolution Astronomy

A new concept promises to fulfill these requirements

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Applications: MAGIC & EUSO

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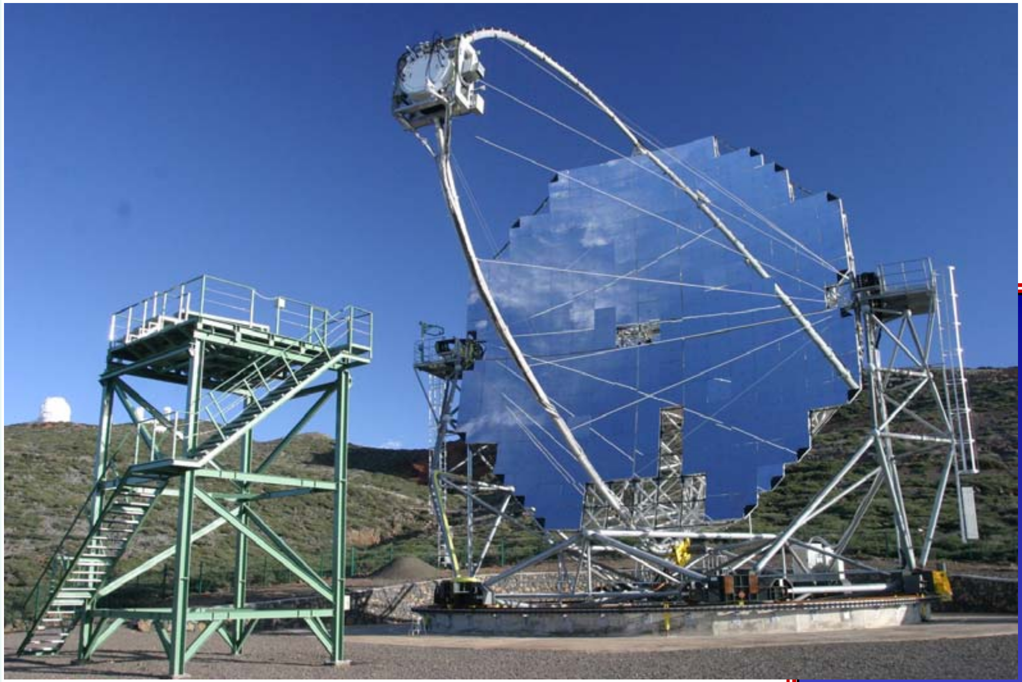

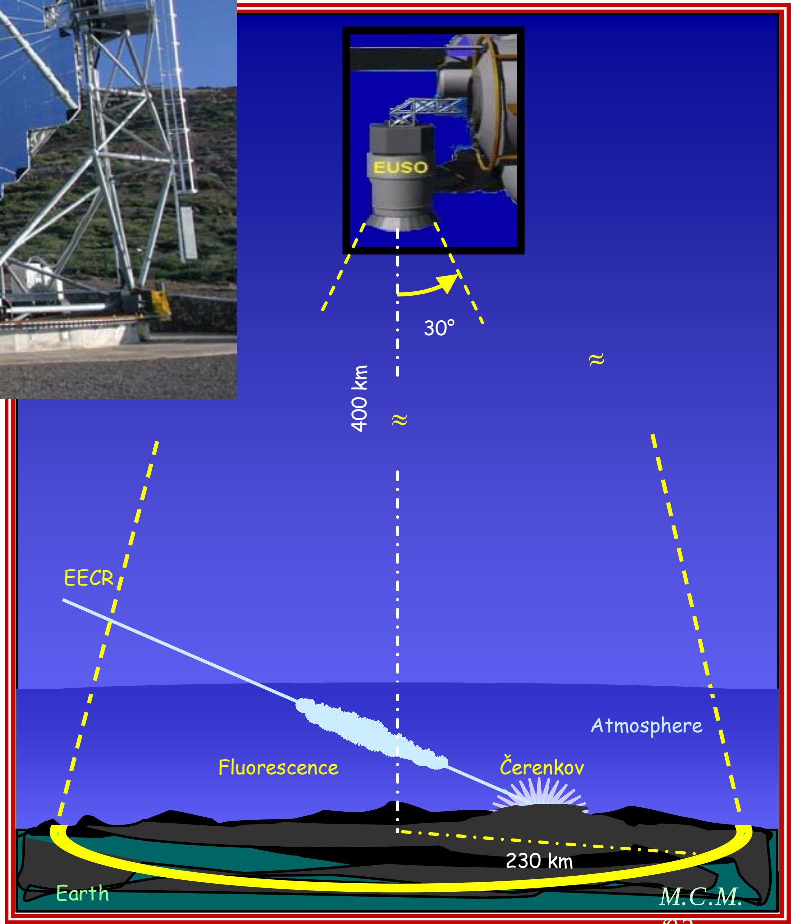

Presently limited by low QE of conventional photomultiplier tubes

Critical: time resolution (<2.5 ns MAGIC)

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Development of Silicon Photomultipliers

SiPMs based on avalanche diode arrays(Geiger Mode) already exist (Dogolshein et al.)

However, the QE is still limited (~40%) (Front illumination)

By combining an avalanche structure with a silicon drift diode some shortcomings of existing Silicon Photomultipliers can be overcome:

- High Quantum Efficiency due to backside illumination (100% fill factor).
- High Sensitivity at short wavelengths due to avalanche trigger by electrons instead of holes.
- Large area devices with low area and low capacitance multiplication region.
- Good time resolution due to field shaping of drift region.

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SiPM concept

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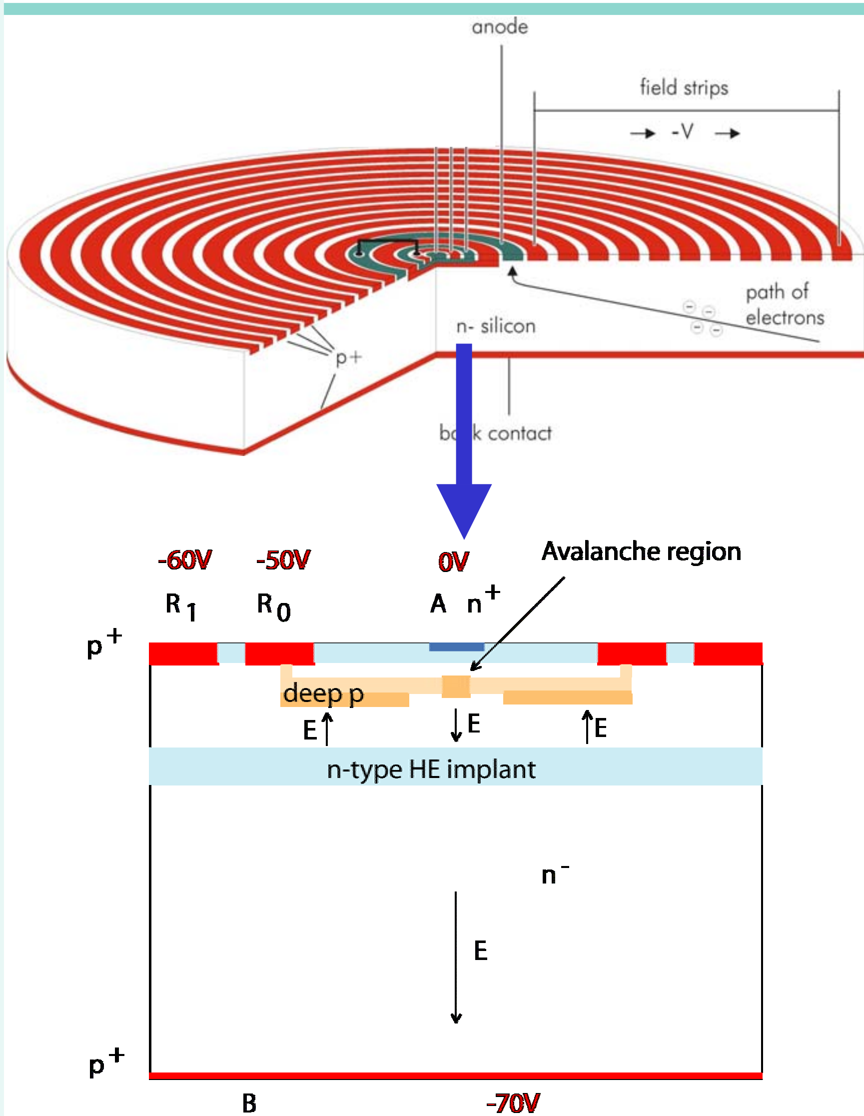

Fig. 1. Concept of the avalanche drift diode

Photons enter through unstructured backside and convert in electron hole pairs.

Electrons drift in the electric field generated by the drift rings to the center.

The deep p implant generates a high field region in which the avalanche multiplication occurs.

The low capacitance of the small avalanche region gives detectable signals at small gain, thus reducing cross talk (due to photon emission)

Advantages of backside illumination

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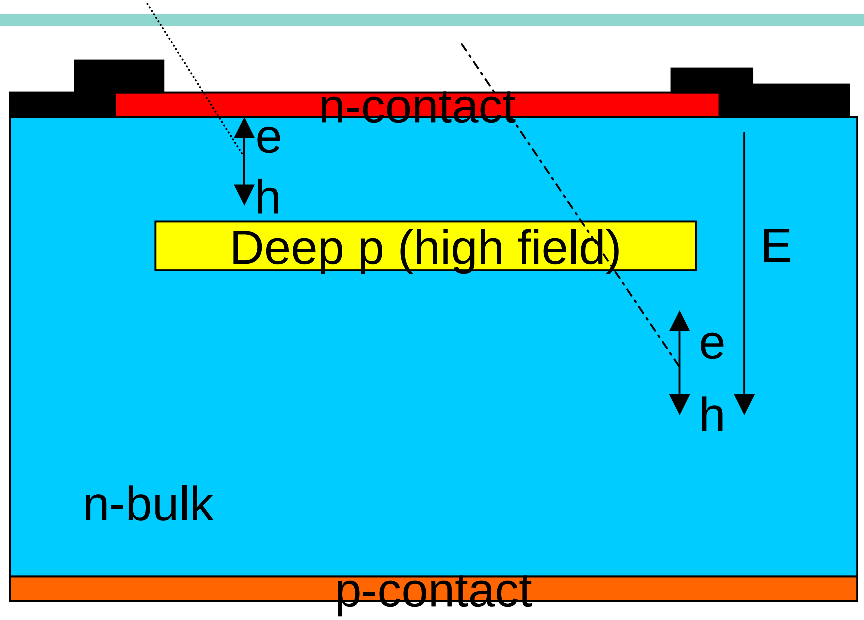
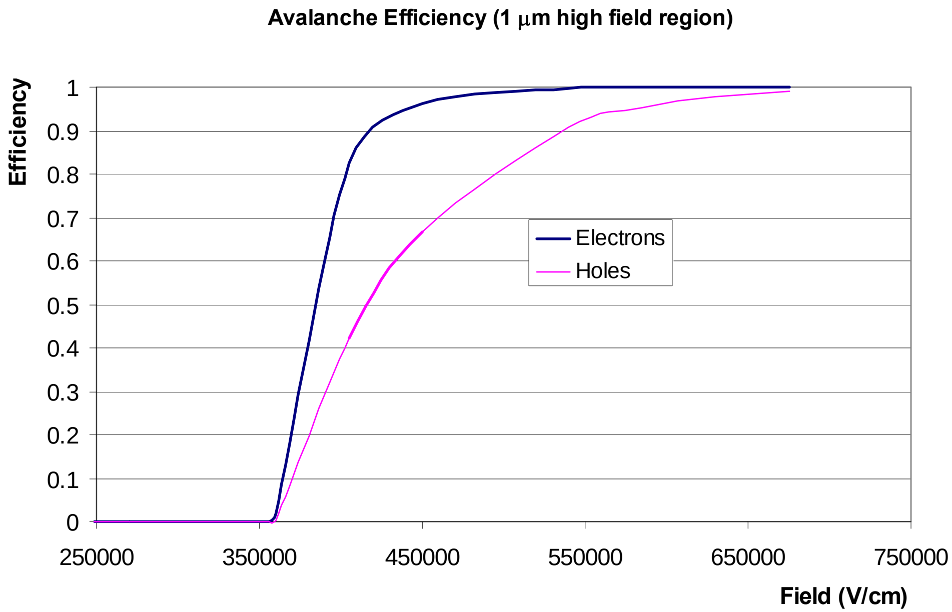
Frontside illumination:

QE limited due to:
-Surface structures
-Short wavelength photons convert close to the surface, before the HF region. Thus only holes can trigger an avalanche, with reduced efficiency





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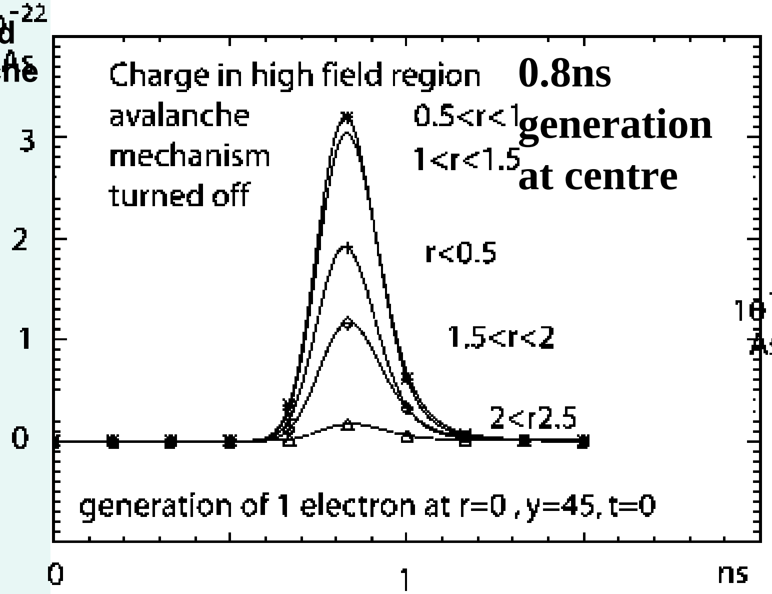
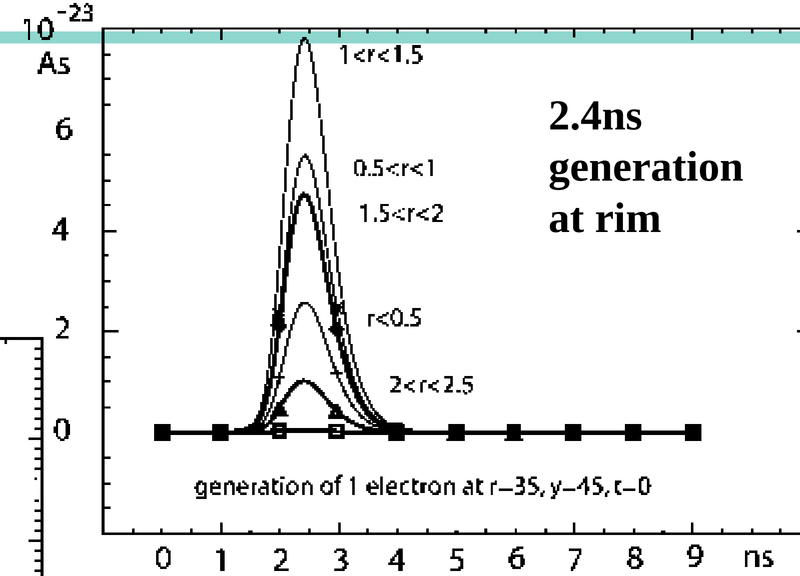
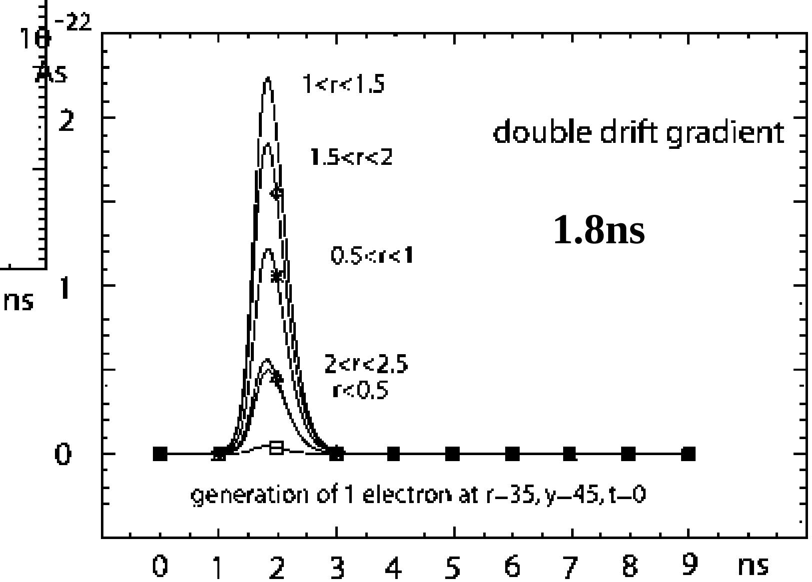
Avalanche drift diode – charge focusing

- » Does all charge focus into homogeneous high field region?
- » Turn avalanche mechanism off
- » Charge density in high field region at different radial regions



Charge collection time 0.9ns
for generation in centre
All charge within r=2





All charge within r=2.5

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SiPM Development

» Conceptual Design and Simulations ongoing

» First test structures to be produced early 2005

» First functional devices end 2005

» Complete SiPM arrays in 2006

» Challenges:

» - Dark rate (control bulk generated leakage currents. Thinning!

» - Cross talk between pixel due to photons emitted in an avalanche and reabsorbed in neighboring pixels (-> low amplification!)

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Conclusions

» New Projects, especially for WHI experiments, are emerging:

» - Silicon Drift Detectors for Muon Cooling

» - DEPFET Pixel Detectors for ILC

» - Silicon Photomultiplier for MAGIC & EUSO

» These projects make use of the production facilities of the HLL, unlike ATLAS SCT, which used mainly design and test facilities

» Remark: The DEPFET project urgently needs support by a strong ILC physics group!

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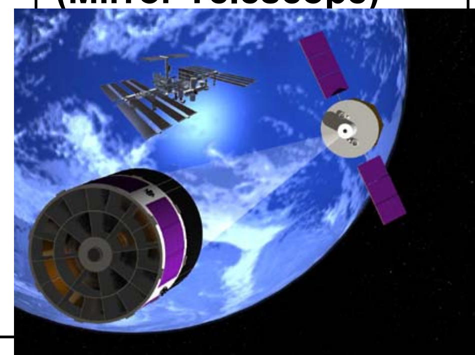
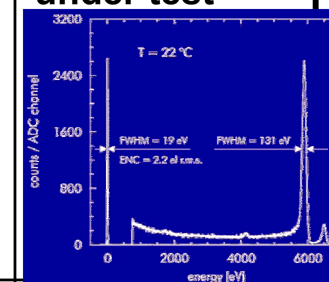
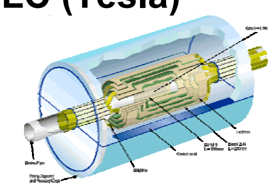
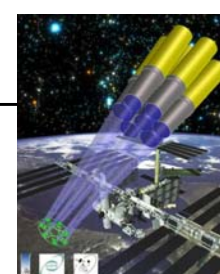
Major Projects

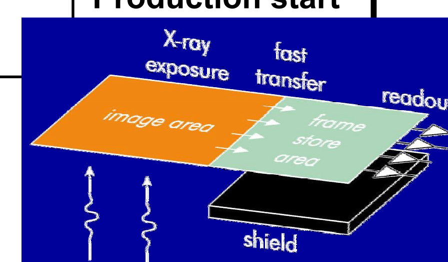
Project	Institutes	Physics	Device	Status
XEUS (X-Ray Evolving Universe Sepctrometer)	MPE ESA	X-Ray Astronomy (Mirror Telescope)	Thick DEPFET Pixel Detector	Small size prototype under test
ILC (Tesla)	WHI Bonn Mannheim	E+ E- linear collider Vertex Detector	Thin DEPFET Pixel Detector	Thick Prototypes under test
DUO	MPE NASA	X-Ray Astronomy (Mirror Telescope)	Frame store pnCCD	Prototype existing Production start
Rosita	MPE ESA	Like DUO	Frame store pnCCD	











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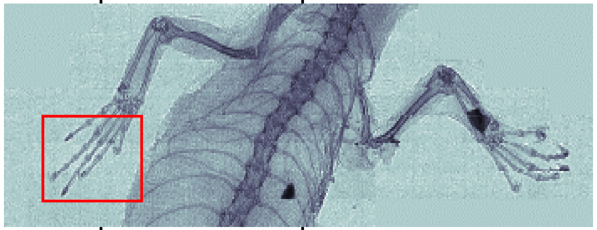
More Projects....

HTRA High Time Resolution Astrophysics	MPE MPIA MPA	Observation of rapidly varying objects (Ground based Optical Telescope)	pnCCD	Produced together with DUO
Sensors for adaptive optics	MPE ESO	Rapid corrections for change in the atmosphere	pnCCD	Produced together with DUO
Compton Camera	MPE Siegen Essen Bonn Jülich Milano	Medical imaging, pharmaceutical investigations	Controlled Drift Detector	Produced together with DUO
SIDDHARTA	MPE Frascati Wien	Investigation of kaonic atoms (X-Ray Spectroscopy)	Drift detectors ~200 of 1cm2	Start July 2004



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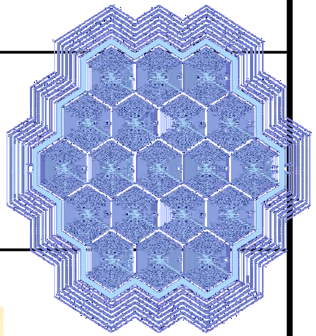
More Projects.... (not complete)

Muon collider	WHI	Muon Cooling By friction (De/dx)	Silicon drift detector (simila to Siddahrta)	Samples for test setup delivered
DRAGO	MPE Milano	Medical imaging	Multicell Silicon drift detector	Available
FELIX	MPE Milano	X-ray fluorescence (art)	Drift detectors	Available
X- and Gamma ray imaging spectroscopy	MPE	Gamma and high energy X-ray detection	Drift detectors	Available
MAGIC (EUSO)	WHI	Air shower telescope	Si-Photomultiplier (avalanche)	Design phase



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