





## Application of DEPFET pixels in High Energy Physics

Julia Furletova University of Bonn

5 April 2012, DESY, Hamburg



### **DEPFET History**



- 1986  $\rightarrow$  proposed by J. Kemmer and G. Lutz (MPI)
- $1990 \rightarrow experimentally verified$
- $1995 \rightarrow +NRW$  (Bonn) readout electronic design
- 1999  $\rightarrow$  Proposal for ILC pixel detector + R&D
- $2008 \rightarrow \text{PXD}$  for Belle II
- $2012 \rightarrow \text{DEPFET}$  for something else?





### DEPFET History/Outline



- 1986  $\rightarrow$  proposed by J. Kemmer and G. Lutz (Munich)
- $1990 \rightarrow experimentally verified$
- $1995 \rightarrow +NRW$  (Bonn) readout electronic design
- 1999  $\rightarrow$  Proposal for ILC pixel detector + R&D
- $2008 \rightarrow \text{PXD}$  for Belle II
- $2012 \rightarrow \text{DEPFET}$  for something else?



## Outline

- DEPFET principle
- DEPFET R&D for ILC
- DEPFET as a vertex detector for BELLE II
- DEPFET for something else ...
- Summary



## DEPFET principle



- Each pixel p-channel FET on a completely depleted bulk (sidewards depletion)
- Charge collection by drift
- A deep n-implant internal gate of the FET- potential minimum for electrons
- The signal charge leads to a charge in a potential of the internal of internal gate, resulting in a modulation of the channel current of the transistor.
- Accumulated charge can be removed by a clear contract.
  - DEPFET combines detection and amplification within one pixel/device( charge-to-current conversion and amplification)
  - The entire bulk is depleted and sensitive to incident radiation(no stitching, 100% fill factor)
  - Fast charge collection (drift)
  - The readout is non-destructive and can be repeated several times
    - Transistor can be switched off but charge collection is still active !
    - potentially low power device
    - Low readout capacitance reduces the noise





#### Low noise measurements

- ➡ Fe<sup>55</sup> spectrum obtained using DEPFET single pixel with 10µs shaping time.
- In lab tests an equivalent noise charge of ENC=1.6 electrons at room temperature has been measured



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Equivalent electronic circuit of single DEPFET pixel "Rolling shutter" readout (see next page)



#### DEPFET readout sequence



### Matrix of DEPFET pixels

All Sources are connected to a common potential

All External gates are connected row-wise to a GATE Switcher

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All Clears are connected row-wise to Clear Switcher



All Drains are connected column-wise to readout chip. Read out all columns in parallel.



All Drains are connected column-wise to readout chip. Read out all columns in parallel.





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#### DEPFET readout sequence

DEPFET readout sequence row selection for readout select row with external ow selection for reset CLEAR SWITCHER GATE SWITCHER gate readout transistor current: I\_sig + I\_ped clear charge from internal gate drain current readout GATE chip SWITCHER SAMPLE CURO CLEAR SWITCHER time

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#### DEPFET readout sequence

DEPFET readout sequence ow selection for readout row selection for reset select row with external **CLEAR SWITCHER** GATE SWITCHER gate readout transistor current: I\_sig + I\_ped clear charge from internal gate again readout transistor current: I\_ped subtract pedestal current select next row drain current readout GATE chip SWITCHER SAMPLE CURO CLEAR SWITCHER time

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## DEPFET R&D for ILC (1999 - ...)

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•pixel size: 20-30  $\mu$ m, spatial resolution of a few  $\mu$ m

•overall ~ few GPixels

•thin sensors ~0.1% X<sub>0</sub> (to reduce material budget)

low power consumption (simple gas cooling)

radiation tolerance: 200 kRad (5 years)

•Occupancy 1%

Candidates for vertex detector:

CCD, ISIS, MAPS, 3D, DEPFET.



#### DEPFET test system





• 64x256 pixels

 $36x24 \,\mu m^2 - 20x20 \mu m^2$ 

- Readout chip CURO (CUrrent Read-Out) processes all columns in parallel
- The second board (S3B) contains : FPGA, ADCs , buffer RAM, USB2.0-PC interface.





#### DEPFET test beam @ CERN



#### *EUDET Telescope and DEPFET DUT First DUT for EUDET telescope*



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#### ILC/Eutelescope software



 LCIO (LiniarCollider I/O): persistency framework and data model that has been adopded as a standard by the international ILC community.
 MARLIN:C++ application framework
 GEAR: geometry description
 RAIDA: interface to ROOT
 Eutelescope: applications for TestBeam



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#### Advantages of the ILC software:

→standard analysis tools and reconstruction software→space for own development→integrated with GRID for data management and processing



### Test beam results









#### **DEPFET** as a vertex detector

## Bellell experiment at KEK



### B-factory in Tsukuba, Japan



#### World record luminosity for e+e- colliders: 2.1x10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup>



- Great success of KEKB/Belle
  - Measurements of CKM matrix elements
  - observation of direct CP violation in B decays
  - Observation of D mixing
- Nobel prize 2008 for verification of Kabayashi-Maskawa mechanism
- Belle  $\rightarrow$  is SM with CKM right ?
- Belle2 → Is SM wrong? Better accuracy → higher luminosity



## KEKB to SuperKEKB

- e⁻/e⁺, 7 GeV & 4 GeV -E\_cm at Y(4s) resonance,(10.58 Ge\ -goal L = 8x10<sup>35</sup> cm<sup>-2</sup>s<sup>-1</sup>



∕.	Machine parameter	HER (KEKB)	LER (KEKB)	HER (SuperKEKB)	LER (SuperKEKB)		
	Vertical beam size	0.94µm	0.94µm	59nm	59nm		
	Beam current(mA)	1188	1637	2600	3600		
	luminosity(cm <sup>-2</sup> s <sup>-1</sup> )	2.1>	×10 <sup>34</sup>	8x10 <sup>35</sup>			

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In the upgraded machine SuperKEKB •40x higher luminosity

- •2x higher currents
- •smaller beams (nano-beams)
- •20x higher (beam-induced) backgrounds
- more radiation damage
- •2ns bunch crossing
- •all detectors upgraded (improve performance)
- •Physics run at 02. 2016



#### Requirements for the Belle II detector

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#### • Higher event rate

- Higher trigger rate (0.5 kHz  $\rightarrow$  20-30 kHz)
- *Higher background (x10-20 compared to Belle)* 
  - Radiation damage and occupancy
  - Fake hits
- The physical goals require a vertex detector with unprecedented performance (~10µm) :
  - $\rightarrow$  low material budget (<0.2 X<sub>0</sub> per layer)
  - high granularity pixel detector

New pixel vertex detector (**PXD**) based on **DEPFET** technology is being developed, using sensor thinned down to 75  $\mu$ m.







### Belle II PXD ladder





- 8/12 ladders for inner/outer layers
- •All silicon module, sensitive area thinned
- Length: 90mm (inner), 123mm (outer)
- 23mm insensitive silicon on both sides
- Insensitive part is used as substrate for ASICs
- ASICs bump bonded to silicon substrate







### Readout ASICs: DCD and DHP



- 64 inputs at 400MHz input rate
- 50kHz input frame rate
- 30kHz trigger rate
- Receive and write raw data to memories (continuously)
- Trigger  $\rightarrow$  read memory and process data
- Pedestal subtraction
  - Static pedestals (update via JTAG)
- Two pass common mode correction
  - First pass: all pixels  $\rightarrow$  find hits (biased)
  - Second pass: average w/o hits  $\rightarrow$  zero-supp.

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- Hit finder & de-randomizing FIFOs
  - → 64 inputs (FIFO 1)
  - ➡ 1 output (FIFO 2)
- Framer
  - Data formatting
  - AURORA protocol

![](_page_28_Picture_0.jpeg)

### Thin DEPFET – the SOI approach

![](_page_28_Picture_2.jpeg)

![](_page_28_Picture_3.jpeg)

![](_page_29_Picture_0.jpeg)

## PXD6 prototyping

![](_page_29_Picture_2.jpeg)

- 8 SOI wafers (50 μm top layer, 400 μm handle wafer)
  - → + 2 reference wafers on std. 450µm material
- Pixel design and material adapted to 50 µm top layer thickness (Vfd≈15V), extensive device simulations to find the right geometry for the optimal electric field shape
- About 100 test matrices in different variations
  - pixel sizes from 20  $\mu m$  to 200  $\mu m$
  - shorter gate length,
  - improved clear structures,
  - various field shapes..
- Technology variations on the wafer level (new dry etch techniques..)
- 4 half-ladders for Belle II with the most promising design options

![](_page_29_Picture_13.jpeg)

![](_page_29_Figure_14.jpeg)

![](_page_30_Picture_0.jpeg)

### Thin DEPFET & DCD

- <sup>90</sup>Sr source
- DCD, 100 ns row readout
- S/N = 17 without optimization of DEPFET voltages

![](_page_30_Figure_5.jpeg)

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![](_page_31_Picture_0.jpeg)

#### Signal measurements <sup>109</sup>Cd

![](_page_31_Picture_2.jpeg)

- 2 DUTs: 32x64 pixels Belle II PXD design, L=6 μm, pixel size 50x75 μm2, same design on front (CURO readout chip)
  - → I : 450 µm standard
  - → II: 50 μm SOI

![](_page_31_Figure_6.jpeg)

![](_page_32_Picture_0.jpeg)

#### Signal measurements <sup>90</sup>Sr

![](_page_32_Picture_2.jpeg)

- I: 450 μm standard
- II: 50 μm SOI

![](_page_32_Figure_5.jpeg)

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![](_page_33_Picture_0.jpeg)

![](_page_34_Picture_0.jpeg)

### Belle II DEPFET-PXD Summary

- DEPFET is the baseline technology for Belle II PXD
- The high-precision, low mass DEPFET Pixel Detector is in the construction phase
- The first thinned sensor prototypes are currently being tested
  - target read out time of 100ns/row is achieved
  - test shows that thin DEPFET have expected performance.

![](_page_34_Picture_7.jpeg)

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![](_page_35_Picture_0.jpeg)

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## DEPFET ... for something else ???

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![](_page_36_Picture_0.jpeg)

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## DEPFET ... for something else ???

### For transition radiation detection?

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![](_page_37_Picture_0.jpeg)

#### Transition Radiation for relativistic particles

- Transition radiation is produced by a charged particles when they cross the interface of two media of different dielectric constants
- Due to electrodynamic nature of TR the probability to emit one photon per boundary is order of  $\alpha \sim 1/137$
- For high energy charged particles
  - → an energy of TR photons is in X-ray region (2-40keV)
  - rightarrow Total TR Energy  $E_{TR}$  is proportional to the  $\gamma$  factor of the charged particle
  - TR in X-ray region is extremely forward peaked within an angle of  $1/\gamma$ 
    - $\, ^{\prime}\,$  Typically TR photons follows particle track  $\rightarrow$  detected with dE/dx
  - The basic problem in detection of transition radiation photons (TR) is the discrimination of TR from dE/dX energy loss of charged particles.

![](_page_37_Figure_10.jpeg)

![](_page_37_Figure_11.jpeg)

![](_page_37_Figure_12.jpeg)

TR-x-ray

Signal=

Folienstack

![](_page_38_Picture_0.jpeg)

### **Transition Radiation Detectors**

- The classical TRD is based on gaseous detectors filled with Xenon gas mixture to efficiently absorb transition radiation photons, with energy 5-30 keV over a background of dE/dX with energy about 2-3 keV.
- ATLAS TRT uses proportional gas chambers (straws) filled with Xe gas mixture:
  - $\rightarrow$  dE/dx +TR, Cluster discrimination by threshold method.
  - Advantage: they are exist, tested and are working; large areas could be covered.
  - Disadvantage: expensive Xe gas, heavy gas and purification equipment (for space experiments)

![](_page_38_Figure_7.jpeg)

![](_page_38_Figure_8.jpeg)

Simulated event, illustration of clusters from eletron/positron and pion hits – small blue dots are ionizing hits, large red dots are TR hits

![](_page_38_Figure_10.jpeg)

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![](_page_38_Figure_11.jpeg)

![](_page_39_Picture_0.jpeg)

#### Silicon Transition Radiation Detectors

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 Replacing the Xenon based gaseous detectors with modern silicon detectors is complicated by the huge dE/dX of particles in 300-700µm of silicon
 about 100-300keV.

 Another approach to detect TR is to separate dE/dX of particle and TR in magnetic field. In this case, in silicon detectors TR photons and dE/dX are registered in different strips or pixels

 This method requires a large and heavy magnet and additionally is limited by particle momentum: the magnetic field should be able to move a particle from TR by at least one pixel of a silicon detector.

 In 2000 B. Dolgoshein proposed a design for ILC/TESLA detector (see proposal for ILC/TESLA detector LC-DET-2000-038)

Due to a number of limitation this method up to now has been tested only in test beams.

![](_page_39_Figure_8.jpeg)

![](_page_40_Figure_0.jpeg)

- by turning a fully depleted silicon detector (DEPFET) at 30-50° the full path of the particle in one pixel is about 30 µm and therefore dE/dx is a factor 10 less (~10 keV) and comparable with transition radiation energy.
- in addition 10-30 points of dE/dx measurement on the particle track.
- TR photons are absorbed in the first 2-7 bins (pixels) along the track. This fact of additional ionization from TR photons in the first pixels could be used for particle identification (separation).

- Nowadays the DEPFET substrate can be thinned down to 50 μm.
  - $\rightarrow$  dE/dx will be lower.
  - The drawback of this method is that the TR registration efficiency will be also lower.
  - The advantage is that pixel size could be much lager.

![](_page_41_Picture_0.jpeg)

### Geant4 simulation

![](_page_41_Picture_2.jpeg)

Geant4 (Geant4.9.4.p01)+tuning of simulation → will be available in next Geant4 release

![](_page_41_Figure_4.jpeg)

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![](_page_42_Picture_0.jpeg)

### Geant4 simulation

![](_page_42_Picture_2.jpeg)

![](_page_43_Picture_0.jpeg)

### Test beam at DESY

![](_page_43_Picture_2.jpeg)

- Beam: pure electrons 5 GeV, γ~10000
- Sensor: DEPFET 20x20µm was rotated at 41° (~20 pixels per track)
- Radiator: fibers (fleece) length of 5,10,15 cm, was placed in front of the sensor
- DEPFET module and trigger scintillator were installed on 2 motor stages

#### DESY Setup

![](_page_43_Picture_8.jpeg)

![](_page_43_Figure_9.jpeg)

![](_page_43_Picture_10.jpeg)

![](_page_44_Figure_0.jpeg)

![](_page_45_Figure_0.jpeg)

![](_page_46_Figure_0.jpeg)

47

![](_page_47_Picture_0.jpeg)

### TR angular distribution

![](_page_47_Picture_2.jpeg)

- On the right plot is shown the distance of TR clusters from the particle tack in Y-projection, which represent angular distribution of TR photons and multiple scattering of charged particles
- On the lower left plot is shown the same in 3D
- Two lower right plots represent 2D angular distributions of TR clusters (which are defined as compact cluster with size of 1-4 pixels) for electron with radiator and without radiator.
  - Even without radiation there some clusters are reconstructed. (see next slide)

![](_page_47_Figure_7.jpeg)

-10

-20

-30

-30 -20 -10

0

10 20 30

**Distance**, pixels

![](_page_47_Figure_8.jpeg)

![](_page_47_Figure_9.jpeg)

![](_page_47_Figure_10.jpeg)

20

15

10

![](_page_48_Picture_0.jpeg)

### TR clusters efficiency

- The probability to find TR photon near the track is 53% with radiator and 5% without radiator.
- In 47% of inefficiency includes:
  - Overlapping TR cluster with track
  - Inefficiency cluster search algorithm
  - TR cluster too far from track
  - TR photon energy too high not stopped in silicon
  - ✤ No TR photon for this track

![](_page_48_Figure_9.jpeg)

![](_page_48_Figure_10.jpeg)

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![](_page_48_Picture_13.jpeg)

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![](_page_49_Picture_0.jpeg)

### dE/dx vs cluster length

![](_page_49_Picture_2.jpeg)

- Now back to original idea discrimination of TR photons on the top of dE/dx from particle.
- average dE/dx for each of 20 pixels ( $20x20\mu m^2 41^\circ$ )
- *dE/dx along track without radiator is non-uniform due to diffusion and also depends on pixel size and geometry of DEPFET. Since the energy in each pixel is compared independently , the bin uniformity is not important.*
- Most of the TR energy absorbed in first bins

![](_page_49_Figure_7.jpeg)

![](_page_50_Picture_0.jpeg)

### TR photons absorption

![](_page_50_Picture_2.jpeg)

- Geant simulation of DEPFET shows good efficiency for TR photons absorption
- DEPFET thickness of 450 um at 41 degree gives a total path in silicon about 600 um
  - Almost 100% efficiency for photon energy up to 15 keV

![](_page_50_Figure_6.jpeg)

![](_page_51_Figure_0.jpeg)

50

45

40

50 μ

Si

70 µ

![](_page_52_Picture_0.jpeg)

## Electron identification

![](_page_52_Picture_2.jpeg)

For electron identification we have two geometry options - thin and thick sensor

- Thin sensor
  - ✤ 8-9 modules are needed to achieve a pion rejection factor of ~80 (estimated with Monte Carlo, using likelihood method and artificial neural network for electrons and pions of 100 GeV both. Likelihood shows the better result).
- Thick sensor we have two energy options: High energy and low energy.
  - High energy electrons
    - TR photons follow the particle track
    - TR photons absorbed in fist pixels of DEPFET sensor.
    - Additional ionization from TR photons could be used for electron identification
    - the pion rejection factor of about 100 is achieved with 4-5 layers of radiator+silicon
  - Low energy electrons
    - TR photons have a large enough angular distribution to find a TR cluster separated from track
    - Presence of a TR cluster close to track could be used for particle identification
    - If we have a reconstructed track we can calculate the energy deposition in TR area around the particle pixels and to use it for identification.

"New transition radiation detection technique based on DEPFET silicon pixel matrices", J.Furletova, S. Furletov, NIM-A 2010, doi:10.1016/j.nima.2010.06.322 "Geant4 simulation of transition radiation detector based on DEPFET silicon pixel matrices", J. Furletova, S. Furletov, TRD 2011 conference proceedings, submitted to NIM-A.

![](_page_53_Picture_0.jpeg)

### Talk Summary

- A resolution 1-2 µm has been measured at the test beam.
- Thin 50µm DEPFETs have been produced, tested and showed an expected performance.

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- DEPFET is a baseline for Belle2 vertex detector.
- This project gives a strong push for the DEPFET for future e+e- colliders
- DEPFET as transition radiation detector shows promising results.
  Additionally to electron identification it can provide a high precision tracking.
  Could be used at space missions.
- XFEL, space missions

![](_page_53_Figure_8.jpeg)

![](_page_53_Picture_9.jpeg)

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![](_page_54_Picture_0.jpeg)

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![](_page_54_Picture_2.jpeg)

and

![](_page_54_Picture_4.jpeg)

![](_page_55_Picture_0.jpeg)

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# Backup Slides

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**56** 

![](_page_56_Picture_0.jpeg)

### DEPFET readout sequence

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- Sources of transistors are connected to common potential
- Gates are connected row-wise
- Drains are connected column-wise
- Readout chip processes all columns in parallel
- The SWITCHER chip generates the steering signals for the rows GATE and CLEAR.
- Row-wise readout ("rolling shutter mode")
- DEPFET readout sequence :
  - select row with external gate
  - readout transistor current : I\_sig + I\_ped
  - clear charge from internal gate
  - again readout transistor current: I\_ped
  - subtract pedestal current
  - select next row

![](_page_56_Figure_16.jpeg)

![](_page_57_Figure_0.jpeg)

#### Threshold voltage shift of Gates

![](_page_57_Figure_2.jpeg)

- New DUTs (Test structures)
- Thin oxide
- Expected background from QED processes is ~1.2 Mrad/yr, total ~2 Mrad/yr.

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- V<sub>th</sub> shift now well suited for Switcher chips
- After initial rise, flatout of curve ease adaptive biasing scenario

#### The shift is low and tested up to 5-10 years of lifetime

DEPFE,

![](_page_58_Picture_0.jpeg)

### **DEPFET sidewards depletion**

![](_page_58_Figure_2.jpeg)

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![](_page_59_Picture_0.jpeg)

#### Final TB 2008 resolution

![](_page_59_Picture_2.jpeg)

#### Geometry of the 2008 beam test.

![](_page_59_Figure_4.jpeg)

Fina	r	res	id	ua	ls	and		re	50	lut	ion	S	fr	or	P	rad	JU	e	an	al	ysis	5
				-	-	-	-				-	-		-	-	_	_	-	-		-	-

	Module $0$	Module 1	Module $2$	Module 3	Module 4	Module 5
	CCGME-	CCGME-	SIMCME-	CCGME-	CCGME-	CCGME-
Y resolution $[\mu m]$	-S90K02	-90K02	-S90K00	-S90I03	-S90I00	-90I00
	$32x24 \ \mu m$	$32x24 \ \mu m$	$32x24 \ \mu m$	$24\mathrm{x}24~\mu\mathrm{m}$	$32 \mathrm{x} 24~\mu\mathrm{m}$	$32x24 \ \mu m$
X residual $[\mu m]$	2.9	2.2	2.3	2.0	3.1	3.4
Y residual $[\mu m]$	2.3	1.7	1.7	1.7	2.2	2.6
X resolution $[\mu m]$	2.1	1.6	1.9	1.3	2.6	2.4
Y resolution $[\mu m]$	1.5	1.3	1.2	1.2	1.8	1.7

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### **DEPFET for Belle II**

2 layers: @1.4(2.2) cm

DEPFEN

Pixel

![](_page_60_Figure_2.jpeg)

![](_page_60_Figure_3.jpeg)

Power consumption in sensitive area:  $0.1W/cm^2 => air-cooling sufficient$ 

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![](_page_61_Picture_0.jpeg)

### DEPFET readout sequence

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![](_page_61_Figure_3.jpeg)

![](_page_62_Figure_0.jpeg)

Fig. 7. Two-dimensional distributions of the events: energy deposition E in the detector vs spatial displacement of the center of gravity of the charge  $\Delta x$  for pions (a) and electrons (b). Smearing is enhanced in the case of electrons (b) due to the detection of TR photons.

![](_page_63_Picture_0.jpeg)

### Switcher B

![](_page_63_Figure_2.jpeg)

![](_page_63_Figure_3.jpeg)

- Designed size: 2100μm x 3600 μm
- 32 rows
  - each row with CLEAR and GATE output
  - shift register to enable rows (LVDS)
  - → gate and clear strobe signals (LVDS)
  - sleep and boost states for power saving
- AMS HV technology (max 50V)
- Radiation hard design
  - Chip works after 24.5Mrad irradiation
- floating digital 3.3V supply
- JTAG slow control and boundary scan
  - ✤ 1.8V capable I/Os

![](_page_63_Figure_16.jpeg)

![](_page_64_Picture_0.jpeg)

### DCDB

- Chip size: 3240 μm x 4969 μm
- Total: 416 bumps
  - ✤ 256 analog inputs
  - ➡ 64 digital outputs (8 times 8-bit at 350 MHz) for ADC codes
- 8-bit ADC precision
- Sampling period: ~92 ns (350 MHz)
- Every analog channel contains:
  - Current receiver, based on a trans-impedance amplifier with output resistor, with variable gain and shaping time
  - 8-bit current-mode ADC (two per channel)
- Global circuits:
  - Synthesized digital readout block for ADC-data processing, multiplexing and sorting
  - JTAG
- Single-ended digital outputs for 400 Mbit/s
- Supply current:
  - Analog: 300-500 mA
  - → Digital: 300 mA

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![](_page_64_Figure_18.jpeg)

![](_page_64_Figure_19.jpeg)

![](_page_64_Figure_20.jpeg)

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![](_page_65_Figure_0.jpeg)

![](_page_66_Picture_0.jpeg)

## Radiator length

![](_page_66_Picture_2.jpeg)

- The number of TR photons increased with radiator length.
- 2 pictures represent TR yield for 2 radiator length 10 cm and 15 cm.
  - The typical density of radiator 0.05 g/cm<sup>3</sup>

![](_page_66_Figure_6.jpeg)

![](_page_67_Picture_0.jpeg)

#### Why we would like to measure a TR?

![](_page_67_Picture_2.jpeg)

 $10^{\overline{3}}$ 

Momentum (GeV/c)

10<sup>5</sup>

 $10^{4}$ 

Transition Radiation Detectors (TRD) has the 2 CH<sub>2</sub>-He: d<sub>1</sub>=15µ, d<sub>2</sub>=600µ, N<sub>f</sub>=100 attractive features of being able to separate particles by their gamma factor. 1.75  $e/\pi$  separation in high  $\gamma$  region, where other methods 1.5 are not working anymore. 1.25 Identification of the charged particle "on the flight": without scattering, deceleration or absorption. 1 • Application of TRD in collider experiments: 0.75 → ZEUS, H1, HERMES at HERA (DESY), D0, PHENIX, ATLAS, ALICE... electron 0.5 muon pion TRD in space missions – AMS, PAMELA. 0.25 kaon The basic problem in detection of transition radiation 0 10<sup>2</sup> 10 10 photons (TR) is the discrimination of TR from dE/dX 1 energy loss of charged particles.  $\pi/K$ - Frennung Detektorlänge (m) N w č dE/dx TOF 10<sup>3</sup> 10 γ