R&D on CMOS Sensors for the ILC Vertex Detector

IReS-Strasbourg: A.Besson, G.Claus, C.Colledani, M.Deveaux (GSI), A.Dorokhov, W.Dulinski, M.Goffe, D.Grandjean, F.Guilloux, S.Heini (GSI), A.Himmi, Ch.Hu, K.Jaaskelainen, M.Pellicioli, A.Shabetai, H.Souffi-Kebbati (GSI), M.Szelezniak, I.Valin, M.Winter

DAPNIA-Saclay: M.Besançon, Y.Degerli, N.Fourches, I.Orsini, Y.Li, P.Lutz

DESY & Univ. Hamburg: V.Adler, D.Contarato, E.Fretwurst, T.Haas, J.Hauschildt, R.Klanner, U.Kötz, B.Löhr, C.Muhl, W.Zeuner, P.Luzniak (Univ. Lodz)

R&D on CMOS Sensors for the ILC Vertex Detector

IReS-Strasbourg: A.Besson, G.Claus, C.Colledani, M.Deveaux (GSI), A.Dorokhov, W.Dulinski, M.Goffe, D.Grandjean, F.Guilloux, S.Heini (GSI), A.Himmi, Ch.Hu, K.Jaaskelainen, M.Pellicioli, A.Shabetai, H.Souffi-Kebbati (GSI), M.Szelezniak, I.Valin, M.Winter

DAPNIA-Saclay: M.Besançon, Y.Degerli, N.Fourches, I.Orsini, Y.Li, P.Lutz

DESY & Univ. Hamburg: V.Adler, D.Contarato, E.Fretwurst, T.Haas, J.Hauschildt, R.Klanner, U.Kötz, B.Löhr, C.Muhl, W.Zeuner, P.Luzniak (Univ. Lodz)

OUTLINE

- **Refining the constraints from beamstrahlung**
- **Progress on fast sensors adapted to the inner and outer layers**
- **Detector geometry optimisation**
- **Exploration of fabrication processes**
- **Issue of radiation tolerance**
- **Progress on thinning, cooling and mechanical support design**
- **Outlook**
- **Summary**

Constraints from beamstrahlung

- 1st layer: $\gtrsim$ 5 hits/cm^2/BX (4T; 500 GeV) $\longrightarrow \lesssim$ 1.8·10^{12} e$^{\pm}$/cm^2/yr (safety factor: 3)
  - 2nd layer: 8 times less
  - 3rd layer: 25 times less

- Consequences on Occupancy in 1st layer (L0):

  $\lesssim$ 0.9 % hit occ. in 50 μs (r.o. time of TESLA TDR)

  $\hookrightarrow$ signal spread on $\lesssim$ 4.5–9 % pixels (cluster multiplicity $\sim$ 5-10)

  $\hookrightarrow$ 1) aim for shorter read-out time in L0 than in TDR: $\lesssim$ 25 μs

  (compromise with power dissipation, multiple scattering, ...)

  2) aim for shorter read-out time in L1 than in TDR: $\sim$ 50 μs (vs 250 μs)

  (use tracks extrapolated from L1-4 down to L0)

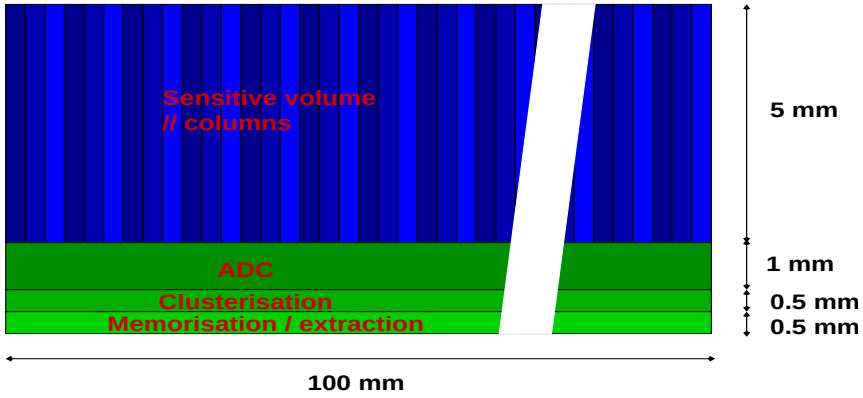
  3) aim for relaxed read-out time in L2, L3, L4: $\lesssim$ 200 μs (vs 250 μs)

- Consequences on Radiation Tolerance in 1st layer (L0):
  - dose integrated over 3 years: $\lesssim$ 5.4·10^{12} e/cm^2 $\longrightarrow \lesssim$ 2·10^{11} n$_{eq}$/cm^2 (NIEL $\sim$ 1/30)

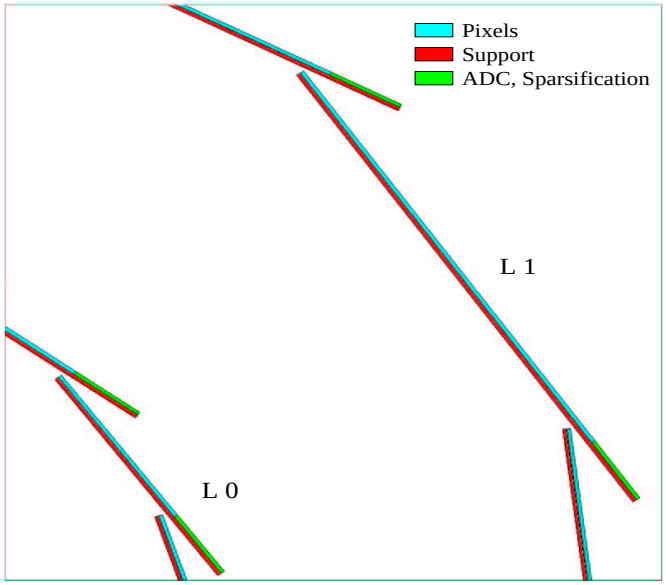
  $>>$ n dose integrated over 3 years much smaller: $\longrightarrow \lesssim$ 3·10^{10} n$_{eq}$/cm^2 (safety factor: 10)

Consequences on Inner Layer Design

- $\lesssim$ 25 μs in L0:
  columns of 256 pixels (20 μm pitch) $\perp$ beam axes
  read out in // at $\sim$ 10 MHz $\longrightarrow$ 5 mm depth
- $\sim$ 50 μs in L1:
  columns of 512 pixels (25 μm pitch) $\perp$ beam axes
  read out in // at $\sim$ 10 MHz $\longrightarrow$ 13 mm depth



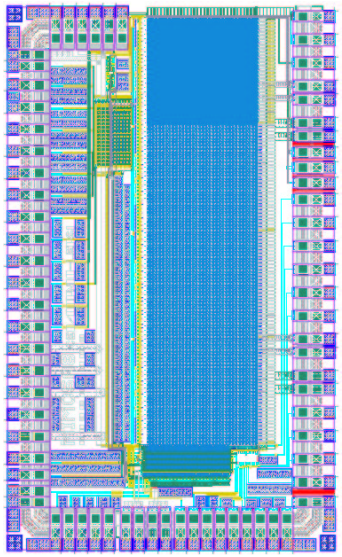
- $\sim$ 2 mm wide side band hosting ADC, sparsification, ...
  $\hookrightarrow$ effect on material budget SMALL:
  b increases by $\sim$ 5-10 %
  ($\sigma_{\mathrm{i.p.}} = \mathrm{a} \oplus \mathrm{b/p} \cdot \sin^{3/2}\theta$)



R&D: Inner Layer Prototype Sensor

▶ MIMOSA-8:

- TSMC 0.25 μm digital fab. process (8 μm epitaxy)
- 32 // columns of 128 pixels (pitch: 25 μm)
- 4 sub-arrays featuring AC and DC coupled on-pixel voltage amplif.
- on-pixel CDS
- discriminator at end of each column

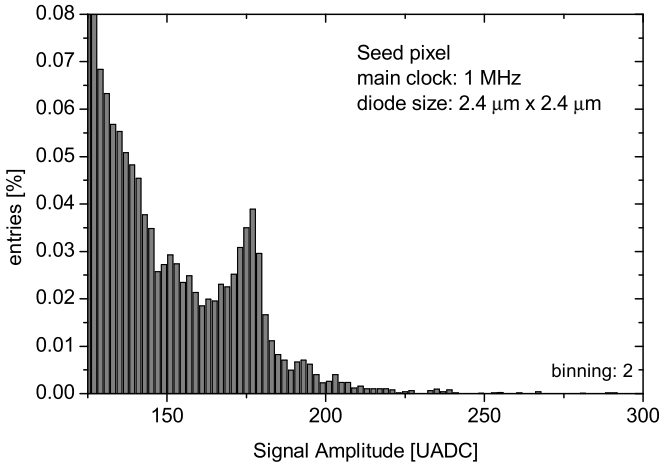


▶ tests with ^{55}Fe source:

◇ conversion factor: 50-110 $\mu V/e^-$,

◇ pixel noise (including CDS): $\sim$ 13 – 18 e^- ENC !

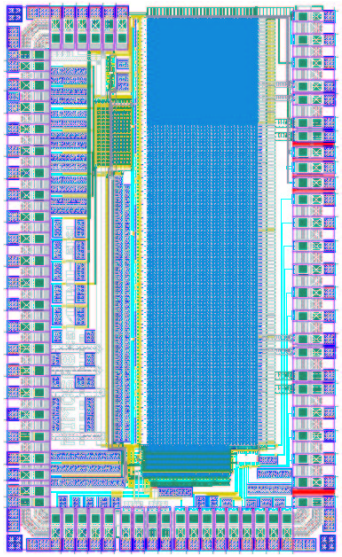
◇ little pixel-to-pixel dispersion ($<$ 10 e^- ENC)!



R&D: Inner Layer Prototype Sensor

▶ **MIMOSA-8:**

- **TSMC 0.25 μm digital fab. process (8 μm epitaxy)**
- **32 // columns of 128 pixels (pitch: 25 μm)**
- **4 sub-arrays featuring AC and DC coupled on-pixel voltage amplif.**
- **on-pixel CDS**
- **discriminator at end of each column**

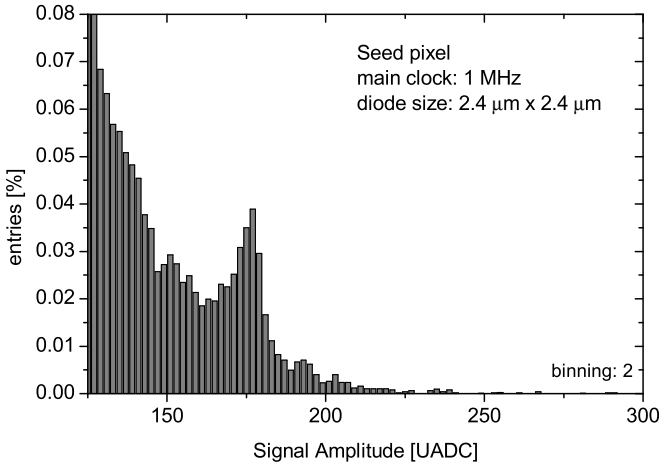


▶ **tests with ^{55}Fe source:**

◇ **conversion factor: 50-110 $\mu V/e^-$,**

◇ **pixel noise (including CDS): $\sim$ 13 – 18 e^- ENC !**

◇ **little pixel-to-pixel dispersion ($<$ 10 e^- ENC)!**



■ **Architecture seems worth extending with integrated ADC, a.s.o.**

R&D: Outer Layer Prototype Sensor

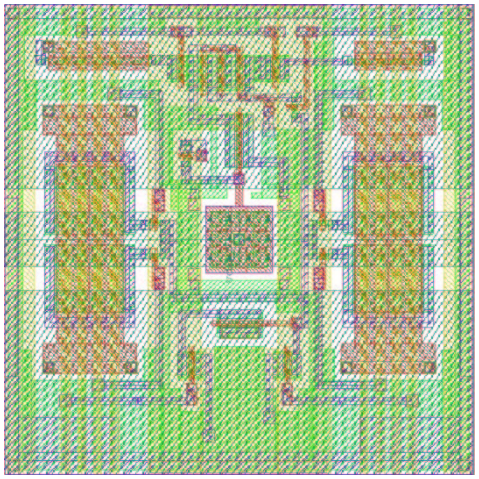
▶ **Two phase micro-circuit architecture, reducing the data flux:**

1) **charge sampled and stored inside pixel during train crossing $\mapsto$ 5 capacitors integrated in each pixel**
2) **signal transfered and processed inbetween trains**

▶ **MIMOSA-12: proto. exploring various types & dimensions of memory cells**

(sent for fab. on 25 March)

- **AMS-0.35 μm technology**
- **4 capacitors/pixel (35 μm pitch)** $\longrightarrow$
- **6 sub-arrays, exploring various MOS capacitors: 50, 100, 200 fF**
- **aim for minimal size capacitors providing satisfactory precision (τ), depending on pitch, i.e. layer, ($\sim$4.6 fF/μm^2)**



▶ **MOS capacitors mandatory:**

$\sim$ 4-5 smaller than poly based ones (cf MIMOSA-6)

Detector Geometry Optimisation

▶ **Geometry close to TESLA TDR: 5 cylindrical layers (R=15 – 60 mm), $||cos\theta|| \leq$ 0.90 – 0.96, BUT:**

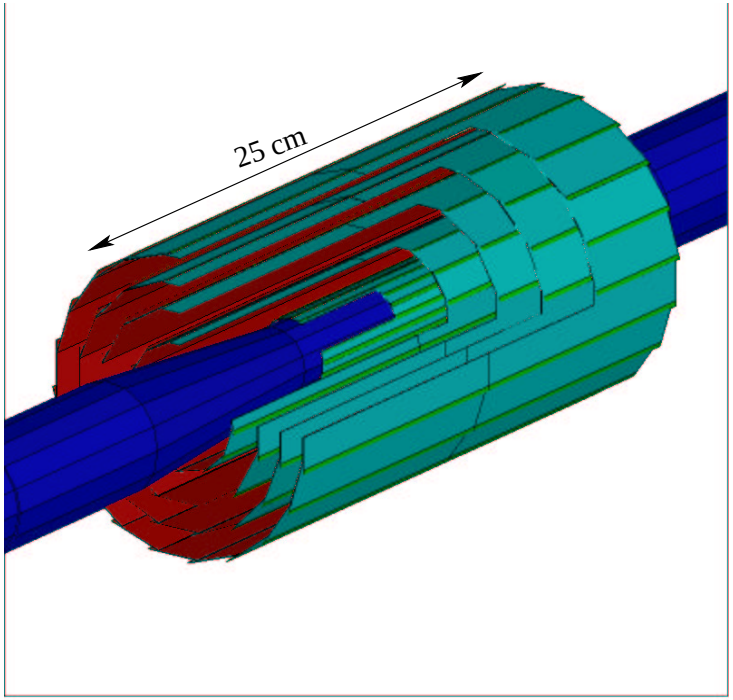
1) variable pixel pitch: 20 μm (L0) $\longrightarrow$ 40 μm (L4)

$\hookrightarrow$ reduced Nb of pixels (300 M) $\longrightarrow$ i.e. reduced data flux and power dissipated

2) shorter read-out time: $\looparrowright$ 25 μs in L0 (instead of 50 μs) $\looparrowright$ 50 μs in L1 (instead of 250 μs)

$\hookrightarrow$ improved capability to cope with beamstrahlung rate

Layer	Radius (mm)	Pitch (μm)	$t_{r.o.}$ (μs)	W_{lad} (mm)	N_{lad}	N_{pix} (10^6)	P^{inst}_{diss} (W)	P^{mean}_{diss} (W)
L0	15	20	25	7	20	25	$<$100	$<$5
L1	25	25	50	15	26	65	$<$130	$<$7
L2	37	30	$<$200	24	24	75	$<$100	$<$5
L3	48	35	$<$200	24	32	70	$<$110	$<$6
L4	60	40	$<$200	24	40	70	$<$125	$<$6
Total					142	**305**	$<$565	$<$**29**



▶ **Average power dissipation $<$ 3 – 30 W (depends on duty cycle: 1/200 – 1/20)**

$\hookrightarrow$ compatible with light cooling system

Exploration of Fabrication Processes

- 13 MIMOSA prototypes designed and fabricated since 1999, in 6 different fab. processes:

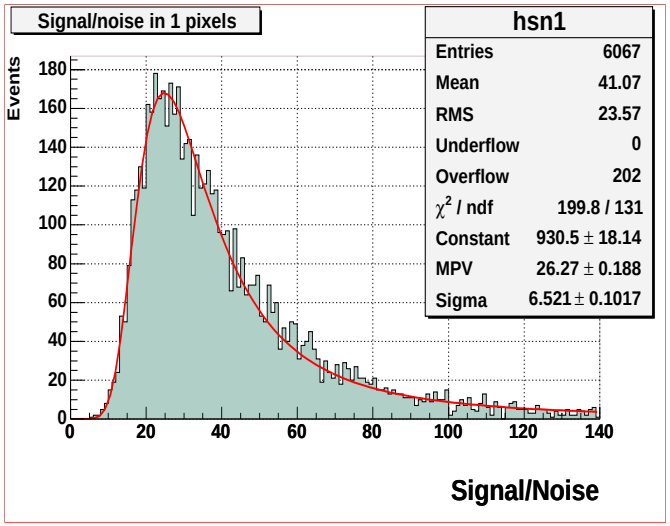
  AMS-0.6μm, AMI-0.35μm, AMS-0.35μm (opto & ordinary), IBM-0.25μm, TSMC-0.25μm

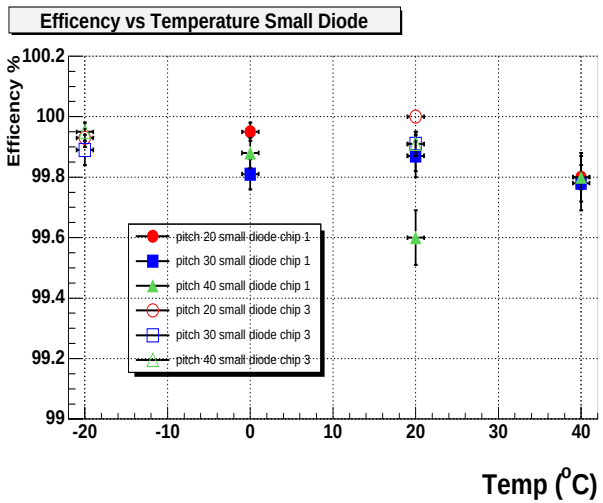
- AMS-0.35 OPTO process tested in 2004 (MIMOSA-9):

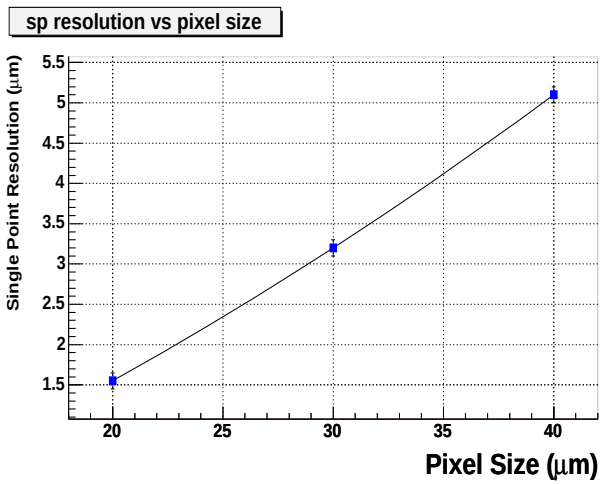
  ◇ pitch: 20, 30, 40 μm ◇ diode size: 3.4x4.3, 5x5, 6x6 μm^2

- Excellent m.i.p. detection performances (assessed with 120 π^- at CERN-SPS):

  ◇ S/N $\sim$ 20-30 (MPV) $\longrightarrow \epsilon_{\mathbf{det}} \sim$ 99–99.9 % ◇ σ_{sp}= 1.5 μm (20μm pitch) $\longrightarrow$ 5 μm (40μm pitch)



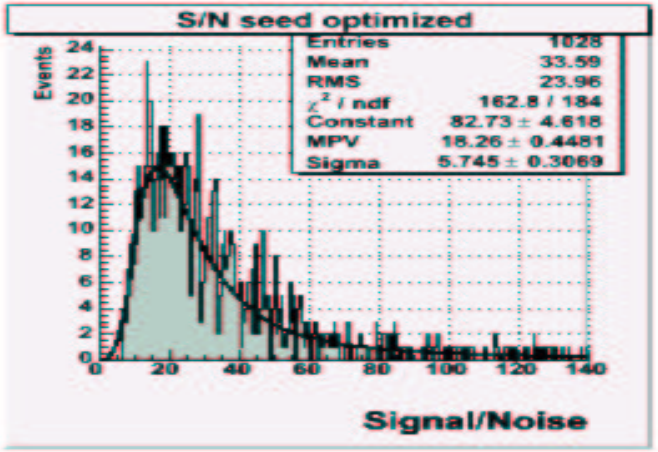




- AMS-0.35μm OPTO: most attractive process tested up to now

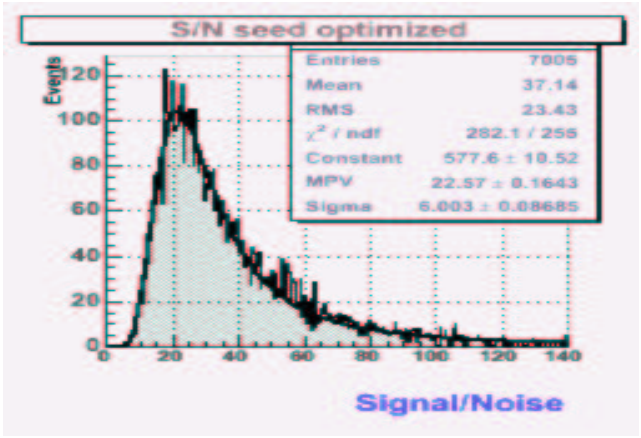
  ↪ baseline for further sensor R&D

Issue of Radiation Tolerance



- Non-ionising radiation $\longrightarrow$ requirement: $\lesssim 3{\cdot}10^{10}\,n_{eq}/cm^2$/3 yrs
  1) MIMOSA-9 exposed to $10^{12}\,n_{eq}/cm^2$ in Dubna
  2) Irradiated chip tested with $\sim$ 6 GeV e^- at DESY

  $\hookrightarrow$ Preliminary results: S/N $\sim$ 18 $\longrightarrow$ $\epsilon_{\mathbf{det}}$ = 99.5 $\pm$ 0.3 %



- "Ionising" radiation $\longrightarrow$ requirement: $\lesssim 5.4{\cdot}10^{12}\,e_{10MeV)}/cm^2$/3 yrs
  1) MIMOSA-9 exposed to $10^{13}\,e^-_{9.4MeV}/cm^2$ in Darmstadt
  2) Irradiated chip tested with $\sim$ 6 GeV e^- at DESY

  $\hookrightarrow$ Preliminary results: S/N $\sim$ 23 $\longrightarrow$ $\epsilon_{\mathbf{det}}$ = 99.3 $\pm$ 0.1 %

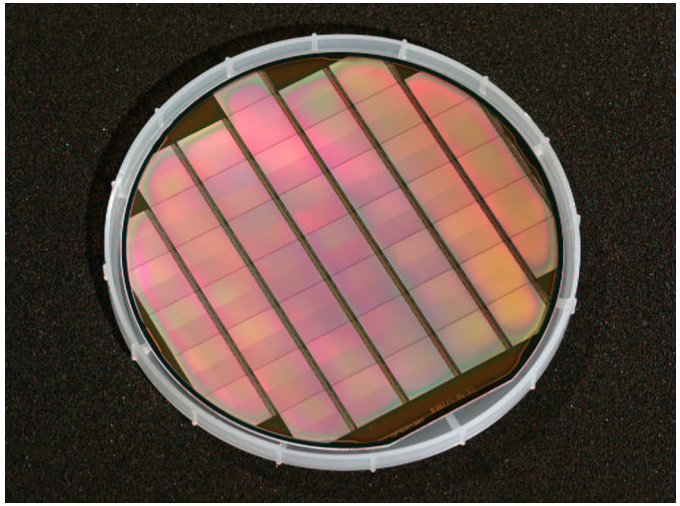
- S/N drops but detection efficiency is still very high

  (before irradiation: S/N $\sim$ 28 and ϵ_{det} = 99.93 $\pm$ 0.03 %)

  $\hookrightarrow$ Sensors seem adapted to ILC irradiation doses (with safety margin !)

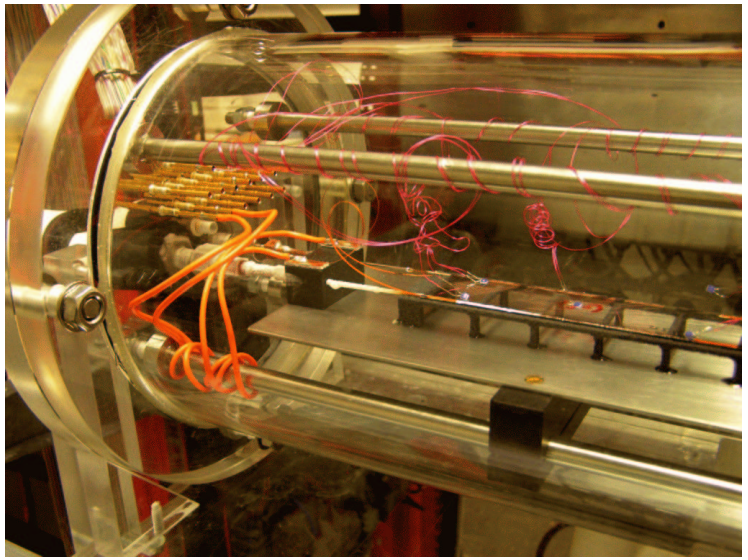
- Sensors should be operated at T $\lesssim$ -10°C (compatible with light cooling system)

Thinning & Ladder Design



- Thinning of MIMOSA-5 sensors (3.5 cm^2) for STAR detector upgrade:
  - 3 wafers thinned via LBNL to 50 $\pm$ 5 μm
  - result satisfactory (after pre-dicing):
    sensors don't brake or wrinkle (but are quite fragile ...)
  - 3 ladder prototypes fabricated ($\gtrsim$ 0.25 % X_0)
    $\longrightarrow$ up to 9 sensors mounted on ladder
  - ladder tests under way (with powered sensors and signal read-out)
  - studies will presumably be extended to ILC vertex detector (including cooling) via LBNL-ILC team
- Thinning trials in Europe:
  - agreement with TRACIT (near Grenoble) to try thinning MIMOSA-5 to 50 $\pm$ 5 μm
  - procedure adjustments under way: first results in May/June

Cooling and Pulsed Powering



- **Set-up installed at DESY for cooling and pulsed powering studies:**
  - ◇ **cooling agent: compressed gas (ex: R134a) close to boiling point**
  - ◇ **fluid flowing through 0.6 mm diameter pipe (0.05 mm wall) in contact with ladder underneath the sensor 2 mm side band**
  - ◇ **heat transfer from ladder to pipe $\longrightarrow$ evaporation (T constant)**
    $\hookrightarrow$ **gas content of fluid rises to 80–90 %**
  - ◇ **next: cooling agent gets compressed and recirculated**
  - ◇ **ladder simulated by glas plate (30 μm thick)**
  - ◇ **side band power source simulated by 2 Al strips evaporated on the glas**
    $\hookrightarrow$ **possibility to generate up to 10 W**
  - ◇ **present status: set-up under completion (T down to -12°C already achieved)**

- **Cooling studies supported by finite element simulation $\mapsto$ ladder temperature profile**

- **Pulsed powering tests of MIMOSA-5 under preparation**

Outlook: Sensor R&D

- **Fast column // read-out for 2 inner layers:**
  - ◇ **Complete MIMOSA-8 tests by Fall 2005: full chain in lab., m.i.p. detection at DESY, rad. tol. (n, e)**
  - ◇ **Start designing ADC $\longrightarrow$ fabricate 1st test structures $<$ end (2005)**
  - ◇ **Next generation (with ADC) early 2006 : 2 versions (TSMC-0.25 and AMS-0.35) – tests through 2006**
  - ◇ **Early 2007: fabricate macroscopic sensors with digital output (optimistic)**
    - $\hookrightarrow$ **EQUIP EUDET TELESCOPE (1st prototype with MIMOSA-5)**
- **Multi memory-cells for 3 outer layers:**
  - ◇ **MIMOSA-12 back from foundry in June $\longrightarrow$ tests (lab) until Autumn '05**
  - ◇ **Next design by end of 2005/ early 2006 $\longrightarrow$ tests till Summer 2006**
  - ◇ **First design with integrated ADC by end 2006**
- **Miscellaneous:**
  - ◇ **Adapt design of micro-circuits to pulsed power operation**
  - ◇ **Start studying sparsification algorithm and design**
  - ◇ **Explore very deep sub-micron processes: IBM-0.13, UMC-0.18, AMS-0.18, ATMEL-0.18 (?), ...**
  - ◇ **Investigate potential effects of beam pick-up $\longrightarrow$ protections ?**

Outlook: Rad. Tol. & System Integration

- **Radiation tolerance:**
  - ◇ Finalise analyses of MIMOSA-9 irradiated with n and e
  - ◇ Assess radiation tolerance (n, e) of each new prototype
  - ◇ Continue investigation of optimal operating temperature (T vs S/N and cooling/mat.budget)

- **Thinning, mechanical support, cooling and pulsed power operation:**
  - ◇ Consolidate 50 μm thinning of MIMOSA-5 (LBNL, TRACIT, others ?)
  - ◇ Try thinning MIMOSA-5 $\gtrsim$ 20-25 μm (2006)
  - ◇ Elaborate on ladder design of LBNL/STAR $\longrightarrow$ LBNL/ILC team
  - ◇ Design 1st ladder prototype (DESY ?, DAPNIA ?, ... $\longmapsto$ EUDET)
  - ◇ Continue cooling and pulsed power studies and tests in DESY

- **Other projects with part of similar requirements:**
  - ◇ Vertex detectors: STAR (2008), CBM, etc. ◇ (EUDET)
  - ◇ Imaging: HPD-CMOS ($\lesssim$ 2007), electron microscopy ($\lesssim$ 2007)

Share of Work

▶ **Work packages:**

- ◇ **sensor design (pixel and read-out, inner and outer layer)**
- ◇ **sensor performance assessment (speed, m.i.p. detection, rad.tol., thinning, power diss., etc.)**
  - ↪ **relies on 4–6 weeks beam tests per year (DESY, CERN)**
- ◇ **sensor thinning: 1) 50 μm 2) 20–25 μm ? stitching ?**
- ◇ **design and assessment of mechanical support: aim for $<$ 0.1 % X_0**
- ◇ **design of light cooling system and certification of pulsed power operation mode**

Laboratory	IReS	DAPNIA	DESY+Univ. Hb	Others
Sensor design	■	■	–	IN2P3, ...
Sensor caracterisation	■	▲	▲	IN2P3, ...
Radiation Tolerance	■	▲	▲	–
Thinning	■	–	△	LBNL
Mechanical Support	–	△	▲	LBNL, (LCFI)
Cooling & pow. pulsing	▲	–	■	–

▶ **Substantial benefit from other groups developing/integrating CMOS sensors on Vertex Detector:**

LBNL for STAR and ILC, RAL, Hawaï, BNL, INFN, ...

SUMMARY

- Rate of e_{BS} revisited $\mapsto$ faster read-out and enhanced radiation tolerance required (w.r.t. TESLA TDR)

- Vertex Detector concept exploiting CMOS sensor advantages:
  - ◇ fast col. // r.o.: 25 μs in L0, 50 μs in L1 $\mapsto$ small mat. budget penalty: b $\nearrow$ by $\sim$ 5–10 %
  - ◇ multi memory-cell pixels with delayed signal transfer and processing in L2, L3, L4
  - ▷ variable pitch: 20 μm (L0) $\mapsto$ 40 μm (L4)
  - ▷ mean power dissipated $\lesssim$ 3–30 W

- Status of sensor R&D:
  - ◇ fast col. // architecture found, with low noise & small pixel-to-pixel dispersion
  - ◇ prototype with 4 memory-cells per pixel being fabricated $\longrightarrow$ explore cell precision vs size
  - ▷ tolerance to 10 MeV e^- (and 1 MeV n) very satisfactory
  - ▷ thinning to 50 μm seems OK

SUMMARY

- Rate of e_{BS} revisited $\mapsto$ faster read-out and enhanced radiation tolerance required (w.r.t. TESLA TDR)

- Vertex Detector concept exploiting CMOS sensor advantages:
  - ◇ fast col. // r.o.: 25 μs in L0, 50 μs in L1 $\mapsto$ small mat. budget penalty: b $\nearrow$ by $\sim$ 5–10 %
  - ◇ multi memory-cell pixels with delayed signal transfer and processing in L2, L3, L4
  - ▷ variable pitch: 20 μm (L0) $\mapsto$ 40 μm (L4)
  - ▷ mean power dissipated $\lesssim$ 3–30 W

- Status of sensor R&D:
  - ◇ fast col. // architecture found, with low noise & small pixel-to-pixel dispersion
  - ◇ prototype with 4 memory-cells per pixel being fabricated $\longrightarrow$ explore cell precision vs size
  - ▷ tolerance to 10 MeV e^- (and 1 MeV n) very satisfactory
  - ▷ thinning to 50 μm seems OK

- Next important steps:
  - ◇ fast col. // sensor with digital output (low power, fast and compact $\sim$4-bit ADC)
  - ◇ continue R&D on multi memory-cell sensor adapted to L2–4
  - ◇ explore fabrication processes with feature size $<$ 0.25 μm
  - ◇ complete study of MIMOSA-5 thinning to $\sim$ 50 μm and try 20–25 μm
  - ◇ complete cooling studies (and pulsed powering)
  - ◇ start designing/making a ladder prototype (equipped with MIMOSA-5 sensors)

▷ Crucial to assess sensor m.i.p. detection performances with beam tests at DESY (and CERN)