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J. Dingfelder, M. Barbero, P. Barrillon, I. Berdalovic, C. Bepin, et al.. Progress in DMAPS developments and first tests of the Monopix2 chips in 150 nm LFoundry and 180 nm TowerJazz technology. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2022, 1034, pp.166747. 10.1016/j.nima.2022.166747 . hal-03664008

HAL Id: hal-03664008

<https://hal.science/hal-03664008>

Submitted on 30 Mar 2023

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1 Progress in DMAPS developments and first tests of the
2 Monopix2 chips in 150 nm LFoundry and 180 nm
3 TowerJazz technology

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15 **Abstract**

16 Depleted Monolithic Active Pixel Sensors (DMAPS) are monolithic pixel de-
17 tectors with high-resistivity substrates designed for use in high-rate and high-
18 radiation environments. They are produced in commercial CMOS processes,
19 resulting in relatively low production costs and short turnaround times, and
20 offer a low material budget. LF-Monopix1 and TJ-Monopix1 are large DMAPS
21 prototypes produced in 150 nm LFoundry and 180 nm TowerJazz technology,
22 respectively, that follow two different design concepts regarding the charge col-
23 lection electrode. Prototypes of both development lines have been extensively
24 tested and characterized over the last years. The second-generation Monopix
25 prototypes, Monopix2, were recently produced. They were designed to address
26 the shortcomings of their predecessors, in particular related to radiation hard-
27 ness and cross talk, and further improve upon their performance. The latest
28 measurements with LF-Monopix1 and TJ-Monopix1 concerning hit efficiency,
29 depletion, and radiation hardness as well as the initial test results of the new
30 Monopix2 prototypes are presented.

31 *Keywords:* Pixel detector, monolithic pixel, DMAPS, CMOS sensor, radiation

33 **1. Introduction**

34 In monolithic pixel detectors, the sensor and the readout electronics form
35 an entity that is fabricated in the same silicon substrate using a commercial
36 CMOS process. As compared to the hybrid pixel detector technology, which
37 is still the standard in current particle physics experiments and provides excel-
38 lent rate capabilities and radiation tolerance, monolithic pixel detectors offer
39 a low material budget and make the labor- and cost-intensive bump bonding
40 process to connect sensor and readout chip unnecessary [1]. A challenge for
41 the design of monolithic detectors is to decouple the charge collection from the
42 high-frequency switching processes of the electronics and to reach sufficiently
43 large charge collection efficiencies in high-radiation environments, as expected
44 for instance at the HL-LHC.

45 Improved radiation tolerance can be achieved with Depleted Monolithic Ac-
46 tive Pixel Sensors (DMAPS) that use high-ohmic substrates ($\rho > 1 \text{ k}\Omega \text{ cm}$) and
47 large enough bias voltages to facilitate full depletion of the substrate (depletion
48 depth $d \propto \sqrt{\rho V_{\text{bias}}}$) and fast charge collection by drift. Large-scale DMAPS pro-
49 totype chips have been designed in various CMOS technologies with integrated
50 fast readout electronics [2–4]. The two DMAPS development lines LF-Monopix
51 and TJ-Monopix, fabricated in 150 nm LFoundry and 180 nm TowerJazz tech-
52 nology, respectively, feature different pixel layouts (in particular concerning the
53 size of the collection electrode), front-end implementations and biasing schemes
54 while using the same readout architecture. They were initially developed to
55 comply with the requirements of the outer layer of the ATLAS Inner Tracker
56 upgrade [5], but have a broad range of potential applications in particle physics,
57 for instance for an upgrade of the Belle II experiment in Japan, and as imaging
58 sensors.

59 During the last few years, the first-generation prototypes LF-Monopix1 and
60 TJ-Monopix1 have been extensively tested and characterized. Improved second-

61 generation prototypes, Monopix2, were submitted for both DMAPS lines in 2020
62 and became available for testing in spring 2021. In this contribution, recent
63 updates on the Monopix1 characterizations and the first test results of the new
64 Monopix2 prototypes are presented.

65 **2. The Monopix chips**

66 LF-Monopix and TJ-Monopix are both fully monolithic pixel designs with
67 the readout electronics completely integrated in the pixel cell, but follow differ-
68 ent concepts for the charge collection electrode. LF-Monopix features a large
69 electrode that surrounds the electronics, while TJ-Monopix has a small collec-
70 tion electrode with the electronics placed outside of the electrode. Both chips
71 use a fully synchronous column-drain readout architecture [6] that is similar to
72 the one used in the FE-I3 readout chip of the ATLAS pixel detector [7]. Charges
73 that are created in the sensitive volume by a traversing ionizing particle are col-
74 lected in the collection electrode, amplified and converted into a voltage pulse
75 that is compared to an adjustable threshold. The leading and trailing edges
76 of the discriminator output determine the time of arrival and the total length
77 (time over threshold) of the pulse using a 40 MHz clock.

78 *2.1. LF-Monopix design (LFoundry 150 nm)*

79 LF-Monopix1 is the first large-scale DMAPS prototype with a large collec-
80 tion electrode and fully integrated electronics for fast standalone readout [8].
81 The pixel matrix has a size of $1 \times 1 \text{ cm}^2$ and a pitch of $50 \times 250 \mu\text{m}^2$. A cross
82 section of the pixel layout is shown in Fig. 1. The collection electrode is formed
83 by a large deep n-implant that contains the in-pixel electronics, while being
84 isolated from it through a p-type implant. A p-type substrate with a high resis-
85 tivity ($> 2 \text{ k}\Omega \text{ cm}$) constitutes the sensitive volume, which can be fully depleted
86 if a large enough bias voltage is applied. After wafer thinning and back-side
87 processing, substrate thicknesses ranging from $750 \mu\text{m}$ down to $100 \mu\text{m}$ are
88 available. The large electrode and strong electric field lead to short drift times

89 that result in a high charge collection efficiency and a good radiation tolerance.
90 On the other hand, the large sensor capacitance (~ 400 fF) related to the size
91 of the electrode compromises the noise and rise time of the signal (more power
92 for the analog front-end is needed to maintain a good timing performance) and
93 requires special design efforts to reduce cross talk from digital activity into the
94 sensing node. Detailed results of the characterization of LF-Monopix1 can be
95 found in Refs. [2, 9–12].

96 The successor chip LF-Monopix2 has a size of 1×2 cm², i.e. full column
97 length, and a smaller pixel pitch of 50×150 μm^2 . The pixel matrix takes up
98 82% of the chip area, the rest is occupied by guard rings, decoupling capacitors
99 and peripheral circuitry at the top and bottom of the chip. Due to the smaller
100 pixel size and hence reduced capacitance ($\sim 250 - 300$ fF) an improved signal-
101 to-noise ratio and a better timing performance are expected. A problem with
102 spurious signals caused by cross talk related to switching of the digital read
103 signal that was observed with LF-Monopix1 was addressed by improving the
104 substrate potential connection inside the pixel and the shielding of the sensing
105 node from transients in V_{DD} lines caused by fast switching signals. A fast
106 and radiation-hard combination of preamplifier and discriminator was chosen
107 as main front-end implementation, based on performance measurements of the
108 first prototype. In addition, variations of such front-end and the chip's tuning
109 circuitry were designed to further improve the timing and threshold dispersion.
110 The matrix is divided into three main submatrices that include different charge
111 sensitive amplifier (CSA) designs. One of the submatrices is further subdivided
112 into four regions with different CSA feedback capacitances (1.5 fF or 5.0 fF),
113 local threshold tuning schemes (unidirectional or bidirectional) and pixel-level
114 logic. The pixel design of LF-Monopix2 features rounded corners for reduction
115 of the electric field on the edges, which together with an optimized guard-ring
116 design improve the breakdown behavior of the sensor.

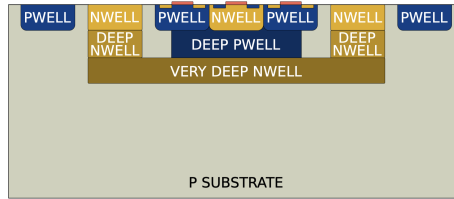


Figure 1: Schematic pixel cross section of LF-Monopix. The deep n-implant forms the charge collection electrode.

117 *2.2. TJ-Monopix design (TowerJazz 180 nm)*

118 The TJ-Monopix series is based on a small collection electrode design [12–
 119 14]. The TJ-Monopix1 chip has an area of $1 \times 2 \text{ cm}^2$ and a pixel pitch of
 120 $36 \times 40 \mu\text{m}^2$. A small n-well is used as collection electrode and separated from
 121 the area where the in-pixel electronics is implemented (Fig. 2). A $25 \mu\text{m}$ thick
 122 p-type epitaxial layer with a resistivity of more than $1 \text{ k}\Omega\text{cm}$ grown on a low-
 123 resistivity substrate serves as sensitive volume. A deep p-well shields the n-wells
 124 of the PMOS transistors and isolates them from the charge collection node, thus
 125 facilitating full CMOS logic. One of the main advantages of this pixel geometry
 126 is the small sensor capacitance ($\sim 3\text{--}4 \text{ fF}$), which facilitates low noise levels and
 127 fast timing while keeping the power consumption minimal. In addition, cross
 128 talk is substantially reduced. However, the small-electrode design is generally
 129 less radiation-hard due to longer drift times and regions with low electric field.
 130 A modified CMOS process [15] with a low-dose n-type layer added over the full
 131 pixel area improves the charge collection and is used to achieve full depletion
 132 of the epitaxial layer with small reverse bias voltages, thus enhancing radiation
 133 hardness [16]. Since the hit efficiency after radiation damage turned out to be
 134 still too low, additional implant modifications (n-gap or extra deep p-well) for
 135 lateral field enhancement [17] or the use of a thick Czochralski substrate to
 136 obtain a larger charge signal [18] were implemented and tested. Their effect is
 137 discussed in Section 3.2.1. The TJ-Monopix1 chip has been characterized in a
 138 series of measurements and the results can be found in Refs. [9, 10, 12].

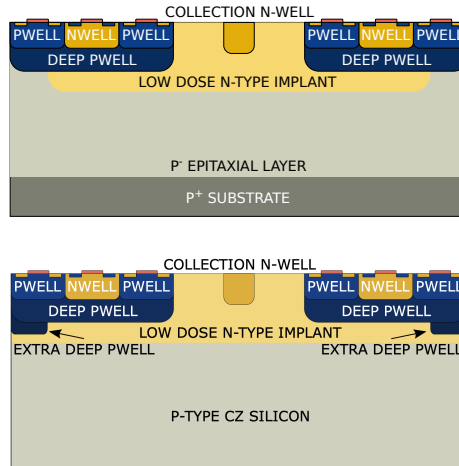


Figure 2: Schematic pixel cross section of TJ-Monopix. The small n-well separated from the readout electronics forms the charge collection electrode. Two process modifications are shown with p-epitaxial layer and n-gap on the pixel edges (top) and with p-type Czochralski substrate and extra deep p-well (bottom).

139 TJ-Monopix2 is a full-size ($2 \times 2 \text{ cm}^2$) chip designed to address the short-
 140 comings of TJ-Monopix1 and provide more sophisticated periphery and LVDS
 141 communication. The active area of TJ-Monopix2, which corresponds to about
 142 70% of the chip area, contains 512×512 pixels with a size of $33.04 \times 33.04 \mu\text{m}^2$.
 143 In addition to the ca. 25% smaller pixel size, which results in faster charge col-
 144 lection, improvements in the analog front end make a reduction of the operating
 145 threshold by about a factor of 3 (below $200 e^-$) possible. An increased coupling
 146 capacitor as well as larger transistors are expected to yield higher gain, lower
 147 noise and improved TID tolerance. The significantly lower threshold enables
 148 the detection of small charge depositions (e.g. because of charge sharing or
 149 trapping) in the thin epitaxial layer. The Monopix2 chip contains four different
 150 front-end flavors: DC-coupled pixels with diode input reset and AC-coupled pix-
 151 els with front-side HV biasing, both with or without an extra cascode transistor
 152 to increase the preamplifier gain. The new front-end circuit design reduces the
 153 noise by approx. 40% and the threshold dispersion by 80 – 90%, depending

154 on the flavor [14]. Additional new functionalities were introduced such as im-
 155 proved pixel masking by using individual in-pixel configuration memory and a
 156 (3-bit) threshold tuning on pixel level to allow for a more uniform threshold
 157 distribution over the matrix.

158 3. Measurements

159 3.1. Results for LF-Monopix

160 3.1.1. Measurements with irradiated LF-Monopix1 chips

161 In a previous measurement with unthinned (750 μm) LF-Monopix1 chips,
 162 the hit efficiency after irradiation with neutrons up to a fluence of $10^{15}n_{eq}\text{cm}^{-2}$
 163 was determined to be 98.9% [2] for a threshold of $1600 e^-$ and a bias voltage
 164 of 130 V. The efficiency has now also been measured for a backside-processed
 165 chip thinned down to 100 μm (of which 85 μm correspond to depletable silicon
 166 substrate). The measurement was performed with a bias voltage of 60 V (160 V)
 167 for the unirradiated (irradiated) case. The hit efficiency maps are shown in
 168 Fig. 3. Efficiencies of 99.6% (99.4%) before (after) neutron irradiation were
 169 obtained for the 100 μm thick sensor. Since this measurement was performed
 170 with the same front-end flavor that serves as default for LF-Monopix2, a similar
 171 efficiency may also be expected for the new chip.

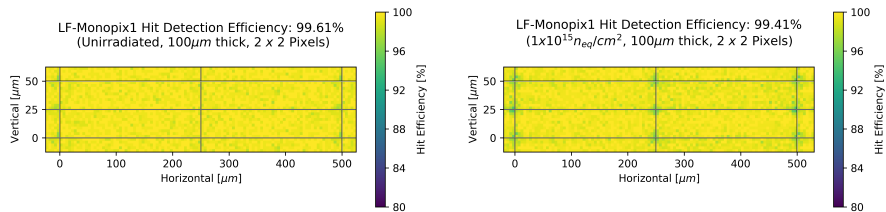


Figure 3: Hit efficiency, mapped onto a 2×2 pixel area, for LF-Monopix1 thinned down to 100 μm , measured for an unirradiated chip (left) and after neutron irradiation up to a fluence of $10^{15}n_{eq}\text{cm}^{-2}$ (right).

172 The full depletion voltage for the 100 μm thick silicon substrate used in both
 173 LF-Monopix chips has been determined from a measurement of the most prob-
 174 able value of the deposited charge distribution for minimum ionizing particles
 175 (MIPs) in dependence of the applied bias voltage. As can be seen in Fig. 4,
 176 full depletion is reached for bias voltages of ~ 15 V before and ~ 150 V after
 177 irradiation. The maximum achievable charge for the neutron-irradiated sample
 178 was found to be somewhat higher than for the unirradiated sample. This could
 179 be due to chip-to-chip variations in thickness after wafer thinning or charge
 180 multiplication occurring in a fully depleted thin sensor after exposure to severe
 181 hadron fluences, but these hypotheses still require further investigation.

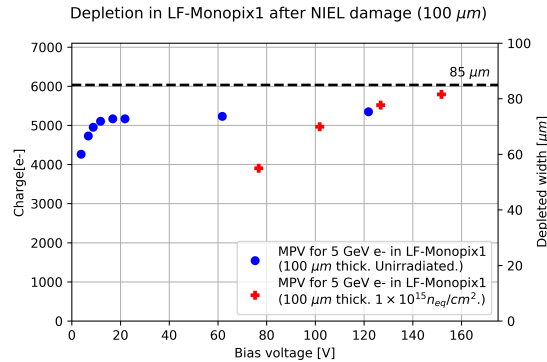


Figure 4: Depletion of LF-Monopix1 (100 μm , unirradiated and neutron-irradiated to $10^{15} n_{eq} \text{cm}^{-2}$) determined from the most probable value (MPV) of the charge distribution of traversing MIPs in dependence of the applied bias voltage.

182 *3.1.2. First measurements with LF-Monopix2: Readout, leakage current, noise*
 183 *and threshold*

184 The new digital in-pixel injection circuitry implemented in LF-Monopix2
 185 was used to validate the readout architecture and the response of the analog
 186 front end. A measurement of the CSA response as a function of injected charge
 187 is shown in Fig. 5. A linear response is observed and a gain of $\sim 20 \mu\text{V}/e^-$
 188 is measured by looking directly at the analog output of the CSA. The correct

189 column-drain readout for the full-length column could successfully be demon-
 190 strated.

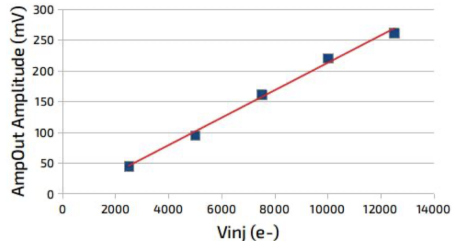


Figure 5: Measured CSA output as a function of injected charge for LF-Monopix2.

191 A measurement of the leakage current as a function of bias voltage was
 192 performed at room temperature for unthinned ($750 \mu\text{m}$ thick) sensors. No
 193 breakdown was observed for LF-Monopix2 up to the maximum applied bias
 194 voltage of 320 V, as can be seen in Fig. 6. For comparison, the breakdown
 195 voltage measured for a LF-Monopix1 chip of the same thickness is about 280 V.
 196 This demonstrates the effectiveness of the optimized guard-ring structure, which
 197 includes an increased ring spacing and an addition of p-type material to the rings
 198 to reduce the voltage drop in each of them.

199 First noise and threshold measurements for LF-Monopix2 were carried out.
 200 Threshold scans were performed by repeatedly injecting varying amounts of
 201 charge and counting the number of registered pixel hits. Threshold and ENC
 202 are extracted from a fit to the measured S-curves. The threshold is defined as
 203 the charge, for which 50% of the injections are observed as hits. The ENC was
 204 determined to be $90 - 100 e^-$ (Fig.7) with a dispersion of $15 - 20 e^-$. The mini-
 205 mum threshold was found to be approximately $1000 e^-$. The noise is about 30%
 206 lower than for LF-Monopix1, which meets the expectation. Since it was mea-
 207 sured with the same front-end flavor for both chips, most of the improvement in
 208 ENC mean and dispersion should come from the reduced detector capacitance.

209 The results of the measurements that have been performed with LF-Monopix2
 210 so far are summarized in Tab. 1 and compared to the expected values and the

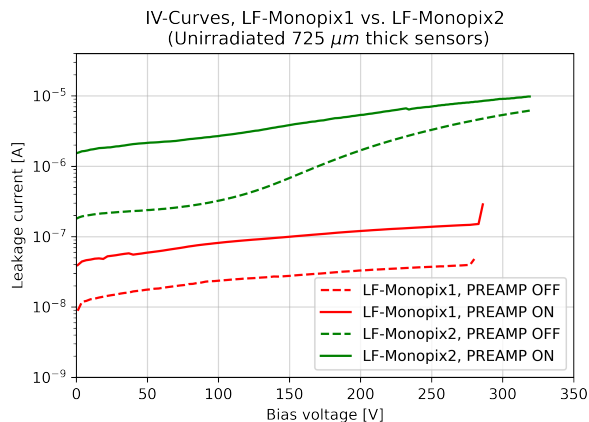


Figure 6: Comparison of I-V curves for LF-Monopix1 and LF-Monopix2 (backside-processed, 750 μm thick sensors). The higher level of leakage current for LF-Monopix2 in this plot is mainly due to the larger number of pixels.

211 ones measured for LF-Monopix1.

212 3.2. Results for TJ-Monopix

213 3.2.1. Hit efficiency of irradiated TJ-Monopix1

214 While the measurements performed with TJ-Monopix1 have generally shown
 215 promising results, radiation hardness is still an issue. It was seen that after
 216 neutron-irradiation up to $10^{15} n_{eq} \text{cm}^{-2}$, the hit efficiency is only about 70% [9],
 217 which is partially due to charge losses in the weak lateral electrical field under
 218 the deep p-well. As mentioned in Sec. 2.2, this problem was addressed by intro-
 219 ducing a gap in the n-implant used for full depletion or an additional p-implant
 220 in this region to enhance the charge collection [17]. Moreover, an increase of
 221 the charge signal would be beneficial and can be achieved through use of a thick
 222 Czochralski substrate instead of a thin epitaxial layer (cf. Fig. 2).

223 Two such sensor variants with (1) 30 μm epitaxial layer and n-gap and (2)
 224 300 μm Czochralski substrate and extra deep p-well were studied. Since the
 225 modifications with n-gap and extra deep p-well serve the purpose of enhancing
 226 radiation tolerance similarly well, as was illustrated in Ref. [19], a comparison

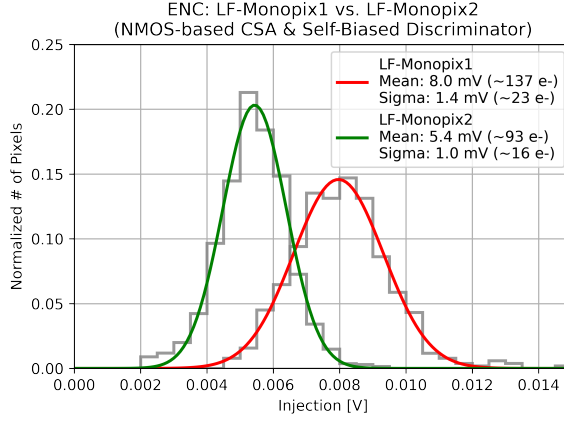


Figure 7: Normalized ENC distribution for LF-Monopix1 and LF-Monopix2.

227 of these two sensor variants mainly corresponds to a study of the effect of the
 228 thickness of the sensitive volume. The two sensor variants were irradiated with
 229 neutrons at the TRIGA reactor in Ljubljana and taken to a test-beam campaign
 230 with a 5 GeV electron beam at DESY. The hit efficiency maps, where the
 231 efficiencies obtained for all pixels have been projected onto a 2×2 pixel area,
 232 are shown in Fig. 8. As expected, the charge loss appears mostly in the pixel
 233 corners, where charge sharing is most prominent, while the efficiencies in the
 234 central pixel regions are only reduced by a few percent. The first variant with
 235 $30 \mu\text{m}$ epitaxial layer shows an increased efficiency of 87.1% after irradiation
 236 with neutrons up to $10^{15} n_{eq} \text{cm}^{-2}$, illustrating the improvement due to the n-
 237 gap. The second variant with $300 \mu\text{m}$ Czochralski substrate yields an efficiency
 238 of 98.6%. The larger amount of charge deposited in the thicker sensitive volume
 239 thus leads to the expected significant improvement in hit efficiency. It can thus
 240 be concluded that the sensor can be made efficient after radiation damage by
 241 making the sensitive volume thicker or by lowering the minimum achievable
 242 threshold through front-end optimization.

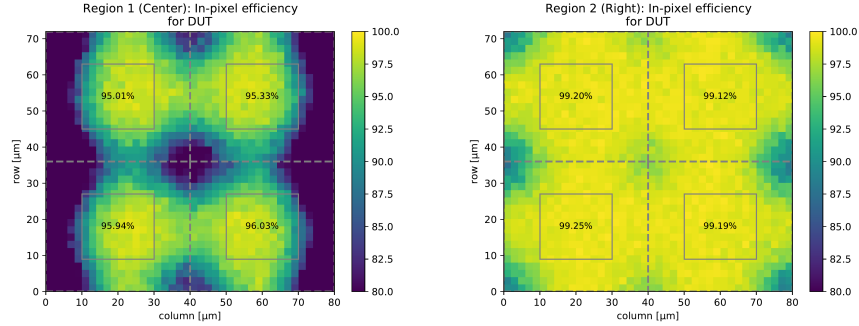


Figure 8: Hit efficiency for TJ-Monopix1 after neutron irradiation to $10^{15} n_{eq} cm^{-2}$, mapped onto a 2×2 pixel area. Two different sensor variants are shown. Left: $30 \mu m$ epitaxial layer and n-gap (threshold: $450 e^-$), right: $300 \mu m$ Czochralski substrate and extra deep p-well (threshold: $490 e^-$).

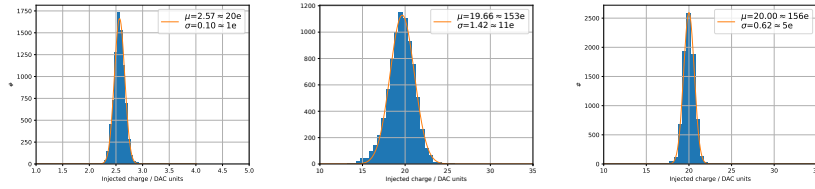


Figure 9: ENC distribution (left) and threshold distribution before (middle) and after local tuning (right) for TJ-Monopix2. The means (μ) and standard deviations (σ) obtained from Gaussian fits are given in the legends in units of electrons.

243 3.2.2. Noise and threshold for TJ-Monopix2

244 To achieve sufficient radiation hardness for a sensor with epitaxial layer,
 245 the threshold needs to be significantly reduced. The in-pixel threshold tuning,
 246 which was implemented as a new feature in TJ-Monopix2, helps to minimize
 247 the thresholds dispersion. Threshold scans were performed in the same way as
 248 explained in Sec. 3.1.2. A mean ENC of $20 e^-$ with a dispersion of $1 e^-$ and a
 249 threshold of $156 e^-$ with a dispersion of $5 e^-$ after threshold tuning are measured,
 250 which represent a significant improvement compared to TJ-Monopix1. Figure 9
 251 compares the threshold distributions obtained before and after tuning. The in-

Table 1: Overview of measured performance parameters for the LF- and TJ-Monopix prototypes. For Monopix2 also the expected values are given. Entries with a dash (–) indicate that these parameters have not yet been measured for the Monopix2 chips.

	LFoundry			TowerJazz		
	Monopix1 measured	Monopix2 expected	Monopix2 measured	Monopix1 measured	Monopix2 expected	Monopix2 measured
Noise	150 – 200 e^-	100 – 150 e^-	90 – 130 e^-	$\sim 20 e^-$	$< 10 e^-$	20 e^-
Threshold dispersion	100 e^-	80 e^-	100 e^-	$\sim 30 e^-$	$< 20 e^-$	5 e^-
Minimum threshold	1500 e^-	1000 e^-	$\sim 1000 e^-$	$\sim 300 e^-$	$< 150 e^-$	$< 150 e^-$
In-time threshold	2000 e^-	1500 e^-	–	$\sim 400 e^-$	250 – 300 e^-	–
Hit efficiency ($10^{15} n_{eq} cm^{-2}$)	$> 99\%$	$> 99\%$	–	$\sim 70\%$ ($> 98\%^*$)	$> 98\%^*$	–

* for n-gap and 300 μm Czochralski substrate.

252 pixel tuning works well and reduces the threshold dispersion by more than a
 253 factor of 2. The minimum achievable threshold has not yet been determined.

254 The results obtained for TJ-Monopix2 are preliminary, but indicate that the
 255 expected improvements can likely be achieved. The measured ENC is somewhat
 256 larger than expected, which is most likely due to cross talk from the digital
 257 readout. An overview of TJ-Monopix measurements is given in Tab. 1.

258 4. Conclusions

259 The second-generation, full-size DMAPS prototypes Monopix2 arrived in
 260 spring 2021 and are currently being tested and characterized. First tests have
 261 shown that their synchronous readout architecture in a full-length column is
 262 fully functional and that sensors and front-ends show the performance expected
 263 from their design improvements. The modifications in pixel layout and front-
 264 end design successfully mitigate cross talk. For TJ-Monopix2 it was shown that
 265 thanks to process modifications radiation hardness can be achieved with small
 266 enough thresholds or the use of a thick Czochralski substrate instead of an epi-
 267 taxial layer. First results show significant improvements of threshold and noise
 268 over the previous version. Further tests and more detailed characterizations of
 269 both chips in test beams and after TID and NIEL irradiation are ongoing.

270 The TJ-Monopix2 prototype has recently been chosen as the baseline for
271 the development of a CMOS sensor for an upgrade of the vertex detector of
272 the Belle II experiment. Its specifications in terms of pixel size, rate capability,
273 timing and radiation tolerance match the requirements for the Belle II upgrade
274 well.

275 **5. Acknowledgments**

276 This project has received funding from the Deutsche Forschungsgemein-
277 schaft DFG (grant WE 976/4-1), the German Federal Ministry of Education
278 and Research BMBF (grant 05H15PDCA9), and the European Union’s Horizon
279 2020 research and innovation programme under grant agreements no. 675587
280 (Maria Sklodowska-Curie ITN STREAM), 654168 (AIDA-2020), and 101004761
281 (AIDAInnova). The measurements leading to these results have partially been
282 performed at the Test Beam Facility at DESY Hamburg (Germany), a member
283 of the Helmholtz Association (HGF).

284 **References**

- 285 [1] R. Turchetta, J. Berst, B. Casadei, G. Claus, C. Colledani, W. Dulinski,
286 Y. Hu, D. Husson, J. Le Normand, J. Riester, G. Deptuch, U. Goerlach,
287 S. Higuieret, M. Winter, A monolithic active pixel sensor for charged particle
288 tracking and imaging using standard VLSI CMOS technology, Nuclear In-
289 struments and Methods in Physics Research Section A: Accelerators, Spec-
290 trometers, Detectors and Associated Equipment 458 (2001) 677–689.
- 291 [2] M. Barbero, et al., Radiation hard DMAPS pixel sensors in 150 nm
292 CMOS technology for operation at LHC, JINST 15 (05) (2020) 05.
293 doi:10.1088/1748-0221/15/05/P05013.
- 294 [3] R. Cardella, E. J. Schioppa, K. Moustakas, MALTA: an asynchronous
295 readout CMOS monolithic pixel detector for the ATLAS High-Luminosity

- 296 upgrade, *Journal of Instrumentation* 14 (06 2019). doi:10.1088/1748-
297 0221/14/06/c06019.
- 298 [4] M. Kiehn, A. Herkert, A. Weber, A. Schöning, A. Miucci, A. Fehr,
299 C. Blattgerste, C. Grzesik, D. M. S. Sultan, D. Immig, D. Forshaw, D. Fer-
300 rere, D. Wiedner, E. Zaffaroni, E. V. Figueras, F. Ehrler, F. Lanni, G. Ia-
301 cobucci, H. Augustin, H. Liu, H. Chen, I. Peric, J. Anders, J. Hammerich,
302 J. Kröger, J. Vossebeld, K. Chen, L. Xu, L. Noehte, L. Huth, M. Vi-
303 cente, M. Benoit, M. Weber, M. Prathapan, N. Berger, S. Dittmeier,
304 S. Sevilla, S. Tang, T. Golling, W. Wu, W. Wong, Performance of the
305 ATLASPix1 pixel sensor prototype in ams aH18 CMOS technology for the
306 ATLAS ITk upgrade, *JINST* 14 (2019) C08013. 7 p. doi:10.1088/1748-
307 0221/14/08/C08013.
- 308 [5] The ATLAS Collaboration, Technical Design Report for the ATLAS Inner
309 Tracker Pixel Detector, Tech. rep., CERN-LHCC-2017-021 (2017).
- 310 [6] E. Mandelli, L. Blanquart, P. Denes, K. Einsweiler, R. Marchesini, G. Med-
311 deler, M. Ackers, P. Fisher, G. Comes, I. Peric, Digital column readout
312 architecture for the ATLAS pixel 0.25 μ m front end IC, in: 2001 IEEE Nu-
313 clear Science Symposium Conference Record (Cat. No.01CH37310), Vol. 1,
314 2001, pp. 600–603 vol.1. doi:10.1109/NSSMIC.2001.1008527.
- 315 [7] I. Perić, L. Blanquart, G. Comes, P. Denes, K. Einsweiler, P. Fis-
316 cher, E. Mandelli, G. Meddeler, The FEL3 readout chip for the AT-
317 LAS pixel detector, *Nuclear Instruments and Methods in Physics Re-*
318 *search Section A: Accelerators, Spectrometers, Detectors and Associ-*
319 *ated Equipment* 565 (1) (2006) 178–187, proceedings of the International
320 Workshop on Semiconductor Pixel Detectors for Particles and Imaging.
321 doi:<https://doi.org/10.1016/j.nima.2006.05.032>.
- 322 [8] P. Rymazewski, et al., Development of depleted monolithic pixel sensors
323 in 150 nm CMOS technology for the ATLAS Inner Tracker upgrade, *PoS*
324 *TWEPP-17* (2018) 045. doi:10.22323/1.313.0045.

- 325 [9] I. Caicedo, et al., The Monopix chips: Depleted monolithic active pixel
326 sensors with a column-drain read-out architecture for the ATLAS In-
327 ner Tracker upgrade, *JINST* 14 (06) (2019) C06006. doi:10.1088/1748-
328 0221/14/06/C06006.
- 329 [10] C. Bepin, et al., DMAPS Monopix developments in large and
330 small electrode designs, *Nucl. Instrum. Meth. A* 978 (2020) 164460.
331 doi:10.1016/j.nima.2020.164460.
- 332 [11] T. Hirono, et al., Depleted fully monolithic active CMOS pixel sensors
333 (DMAPS) in high resistivity 150 nm technology for LHC, *Nucl. Instrum.*
334 *Meth. A* 924 (2019) 87–91. doi:10.1016/j.nima.2018.10.059.
- 335 [12] K. Moustakas, et al., CMOS Monolithic Pixel Sensors based on the Column-
336 Drain Architecture for the HL-LHC Upgrade, *Nucl. Instrum. Meth. A* 936
337 (2019) 604–607. doi:10.1016/j.nima.2018.09.100.
- 338 [13] T. Wang, M. Barbero, I. Berdalovic, C. Bepin, S. Bhat, P. Breugnon,
339 I. Caicedo, R. Cardella, Z. Chen, Y. Degerli, N. Egidos, S. Godiot, F. Guil-
340 loux, T. Hemperek, T. Hirono, H. Krüger, T. Kugathasan, F. Hügging,
341 C. M. Tobon, K. Moustakas, P. Pangaud, P. Schwemling, H. Pernegger,
342 D.-L. Pohl, A. Rozanov, P. Rymaszewski, W. Snoeys, N. Vermes, Depleted
343 fully monolithic CMOS pixel detectors using a column based readout archi-
344 tecture for the ATLAS Inner Tracker upgrade, *Journal of Instrumentation*
345 13 (03) (2018) C03039–C03039. doi:10.1088/1748-0221/13/03/c03039.
- 346 [14] K. Moustakas, Design and Development of Depleted Monolithic Active
347 Pixel Sensors with Small Collection Electrode for High-Radiation Applica-
348 tions, Ph.D. thesis, Rheinische Friedrich-Wilhelms-Universität Bonn (Sep.
349 2021).
350 URL <https://hdl.handle.net/20.500.11811/9315>
- 351 [15] W. Snoeys, G. Aglieri Rinella, H. Hillemanns, T. Kugathasan, M. Mager,
352 L. Musa, P. Riedler, F. Reidt, J. Van Hoorne, A. Fenigstein, T. Leitner,

- 353 A process modification for CMOS monolithic active pixel sensors for en-
354 hanced depletion, timing performance and radiation tolerance, *Nuclear*
355 *Instruments and Methods in Physics Research Section A: Accelerators,*
356 *Spectrometers, Detectors and Associated Equipment* 871 (2017) 90–96.
357 doi:<https://doi.org/10.1016/j.nima.2017.07.046>.
- 358 [16] H. Pernegger, R. Bates, C. Buttar, M. Dalla, J. van Hoorne, T. Kugath-
359 asan, D. Maneuski, L. Musa, P. Riedler, C. Riegel, C. Sbarra, D. Schae-
360 fer, E. Schioppa, W. Snoeys, First tests of a novel radiation hard CMOS
361 sensor process for Depleted Monolithic Active Pixel Sensors, *Journal*
362 *of Instrumentation* 12 (06) (2017) P06008–P06008. doi:10.1088/1748-
363 0221/12/06/p06008.
- 364 [17] M. Dyndal, V. Dao, P. Allport, I. A. Tortajada, M. Barbero, S. Bhat,
365 D. Bortoletto, I. Berdalovic, C. Bepin, C. Buttar, I. Caicedo, R. Cardella,
366 F. Dachs, Y. Degerli, H. Denizli, L. F. S. de Acedo, P. Freeman, L. Gonella,
367 A. Habib, T. Hemperek, T. Hirono, B. Hiti, T. Kugathasan, I. Mandić,
368 D. Maneuski, M. Mikuž, K. Moustakas, M. Munker, K. Oyulmaz, P. Pan-
369 gaud, H. Pernegger, F. Piro, P. Riedler, H. Sandaker, E. Schioppa,
370 P. Schwemling, A. Sharma, L. S. Argemi, C. S. Sanchez, W. Snoeys,
371 T. Suligoj, T. Wang, N. Wermes, S. Worm, Mini-MALTA: radiation hard
372 pixel designs for small-electrode monolithic CMOS sensors for the High Lu-
373 minosity LHC, *Journal of Instrumentation* 15 (02) (2020) P02005–P02005.
374 doi:10.1088/1748-0221/15/02/p02005.
- 375 [18] H. Pernegger, P. Allport, I. Asensi Tortajada, M. Barbero, P. Barrillon,
376 I. Berdalovic, C. Bepin, S. Bhat, D. Bortoletto, P. Breugnon, C. But-
377 tar, R. Cardella, F. Dachs, V. Dao, Y. Degerli, H. Denizli, M. Dyndal,
378 L. Flores Sanz de Acedo, P. Freeman, L. Gonella, A. Habib, T. Hemperek,
379 T. Hirono, B. Hiti, T. Kugathasan, I. Mandić, M. Mikuž, K. Moustakas,
380 M. Munker, K. Oyulmaz, P. Pangaud, F. Piro, P. Riedler, H. Sandaker,
381 E. Schioppa, P. Schwemling, A. Sharma, L. Simon Argemi, C. Solans
382 Sanchez, W. Snoeys, T. Suligoj, T. Wang, N. Wermes, Radiation hard

383 monolithic CMOS sensors with small electrodes for High Luminosity LHC,
384 Nuclear Instruments and Methods in Physics Research Section A: Accelerators,
385 Spectrometers, Detectors and Associated Equipment 986 (2021)
386 164381. doi:<https://doi.org/10.1016/j.nima.2020.164381>.

387 [19] M. Munker, M. Benoit, D. Dannheim, A. Fenigstein, T. Kugathan,
388 T. Leitner, H. Pernegger, P. Riedler, W. Snoeys, Simulations of CMOS
389 pixel sensors with a small collection electrode, improved for a faster charge
390 collection and increased radiation tolerance, Journal of Instrumentation
391 14 (05) (2019) C05013–C05013. doi:[10.1088/1748-0221/14/05/c05013](https://doi.org/10.1088/1748-0221/14/05/c05013).