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Power Dissipation Studies on n^+-in-n Pixel Sensors

Reiner Klingenberg[1], Silke Altenheiner[1], Daniel Bryan[2,1], Sascha Dungs[1], Andreas Gisen[1], Claus Gößling[1], Bettina Hillringhaus[1], Kevin Kröninger[1], Carolin Ratering[1], Tobias Wittig[3]

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[2] University of Oxford, St Anne's College
[3] CiS Forschungsinstitut für Mikrosensorik GmbH, Erfurt

10th International "Hiroshima" Symposium
on the Development and Application of Semiconductor Tracking Detectors,
HSTD-10, Xi'an, China, 25-29 September 2015

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Power Dissipation Studies on n^+-in-n Pixel Sensors

Carolin Ratering, Verlustleistung in bestrahlten planaren n^+-in-n Siliziumstrukturen, Bachelor Thesis, TU Dortmund, August 2015

Sascha Dungs, Aufbau und Charakterisierung eines Messplatzes für temperaturabhängige Messungen von ATLAS-Pixelsensoren, Bachelor Thesis, TU Dortmund, July 2015

Daniel Bryan, Vacation Laboratory Studentship Report, TU Dortmund, August 2015

Silke Altenheiner, Investigaton of n^+-in-n Planar Silicon Pixel Detectors for Applications in the ATLAS Experiment, PhD Thesis, TU Dortmund, July 2015

Bettina Hillringhaus, Temperture-dependent Measurements of the Leakage Current of irradiated ATLAS n^+-in-n FE-I3 sized Single Chip Sensors, Master Thesis, TU Dortmund, September 2014

Reiner Klingenberg, TU Dortmund University

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Power Dissipation Studies on n^+-in-n Pixel Sensors

Investigated Sensor Samples & Irradiations

Measurement Set-up

Leakage Currents: IV and IT Measurements

Temperature Scaling

Sensor Power Dissipation *vs*. Various Parameters

Temperature, Bias Voltage, Bulk Thickness, Sensor Area

IBL-like irradiations and HL-LHC irradiations

Reiner Klingenberg, TU Dortmund University

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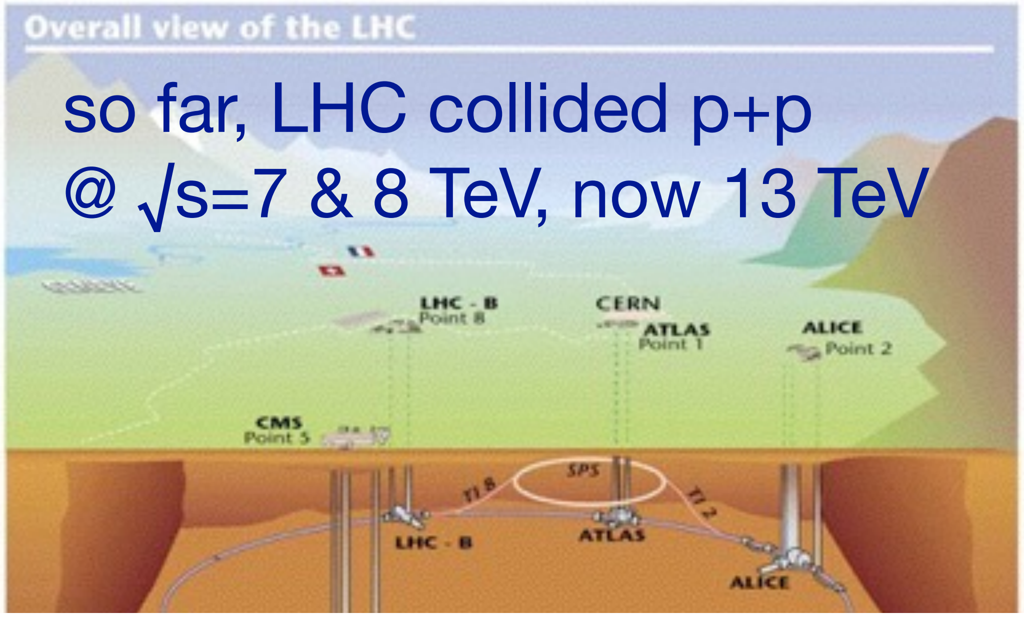
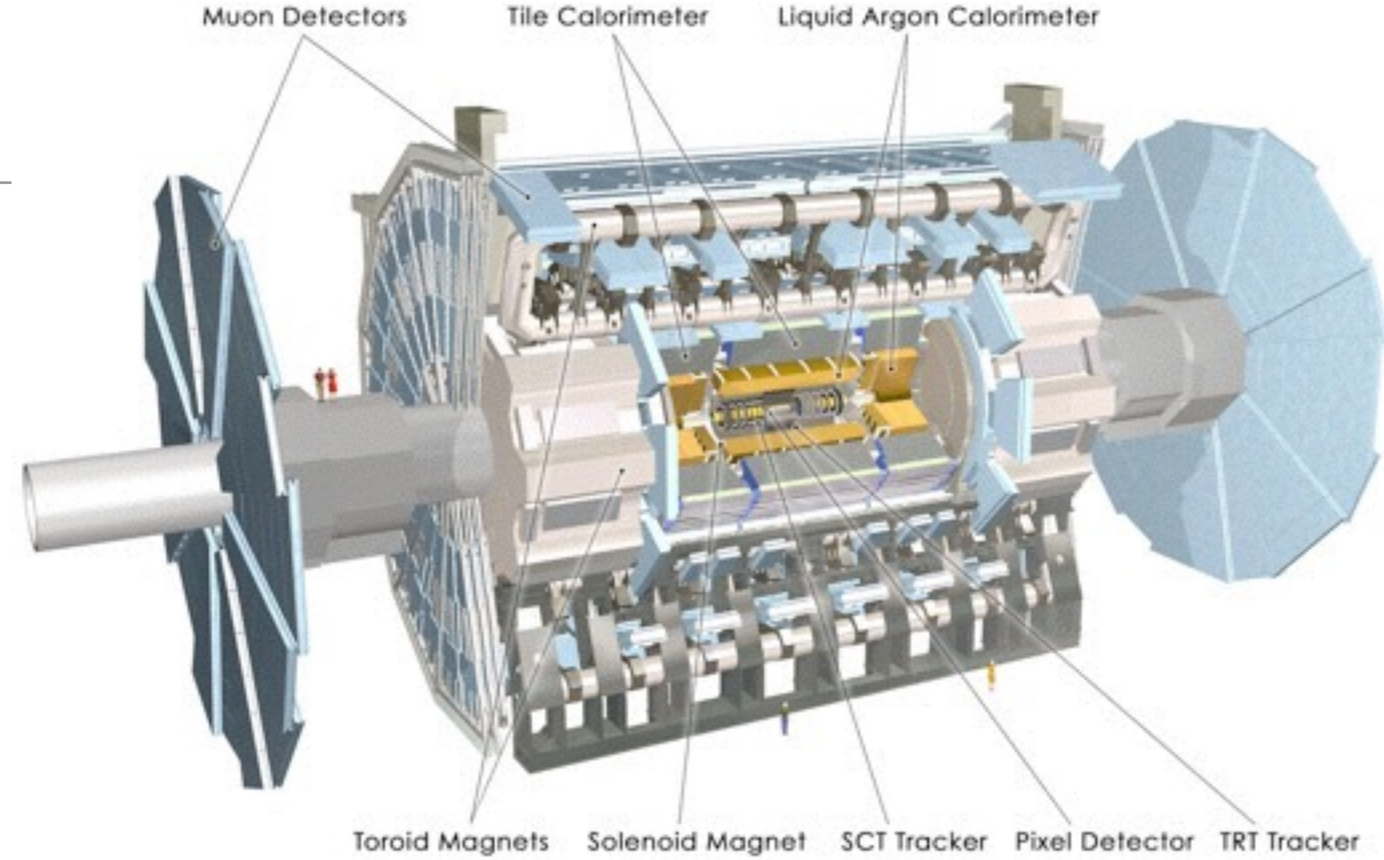
Large Hadron Collider, ATLAS & Pixel-Detector



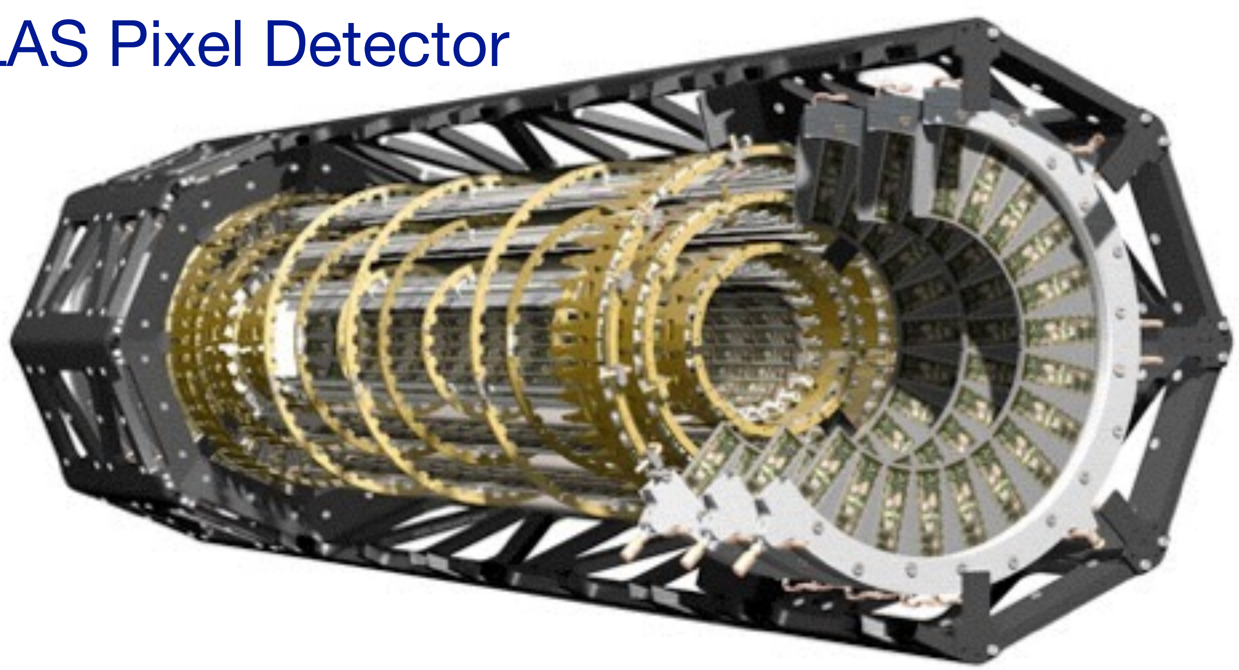
so far, LHC collided p+p
@ $\sqrt{s}$=7 & 8 TeV, now 13 TeV

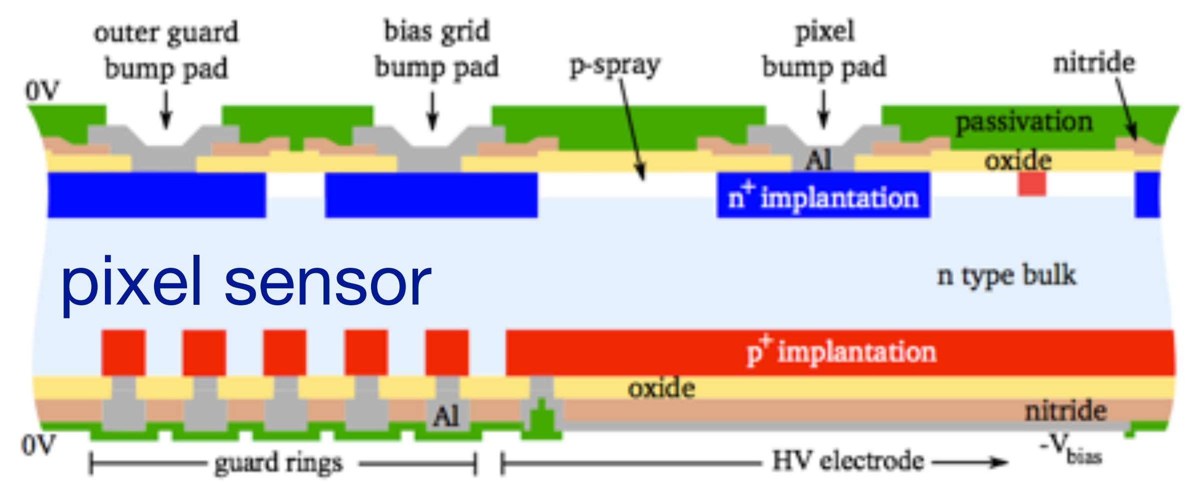


HL-LHC upgrade phase 2

3000 fb^{-1}, 2×10^{16} n_{eq} cm^{-2}

ATLAS Pixel Detector

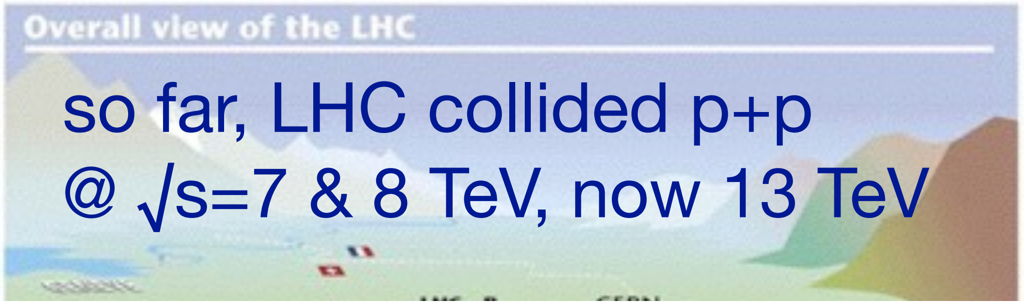




planar n$^+$-in-n DOFZ silicon pixel sensor

3-layer detector: **10^{15} n_{eq} cm^{-2}**, FEI-3: 400×50 μm^2, 250 μm
4th layer (IBL): **5×10^{15} n_{eq} cm^{-2}**, FEI-4: 250×50 μm^2, 200 μm

Large Hadron Collider, ATLAS & Pixel-Detector



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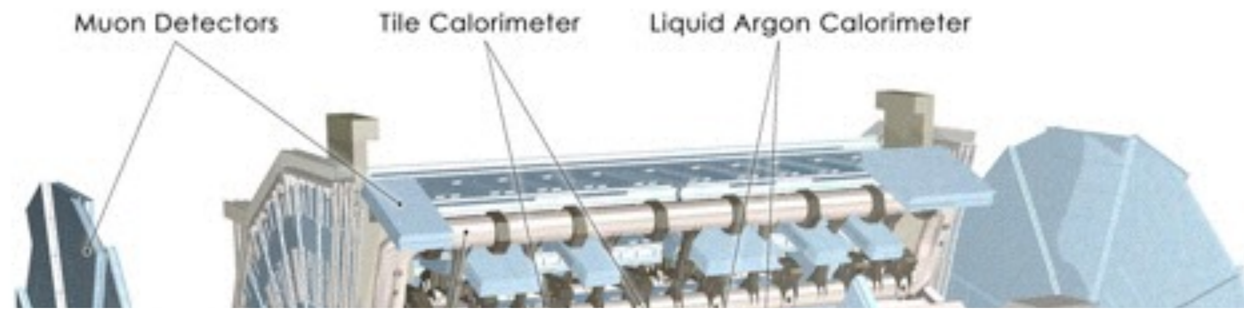
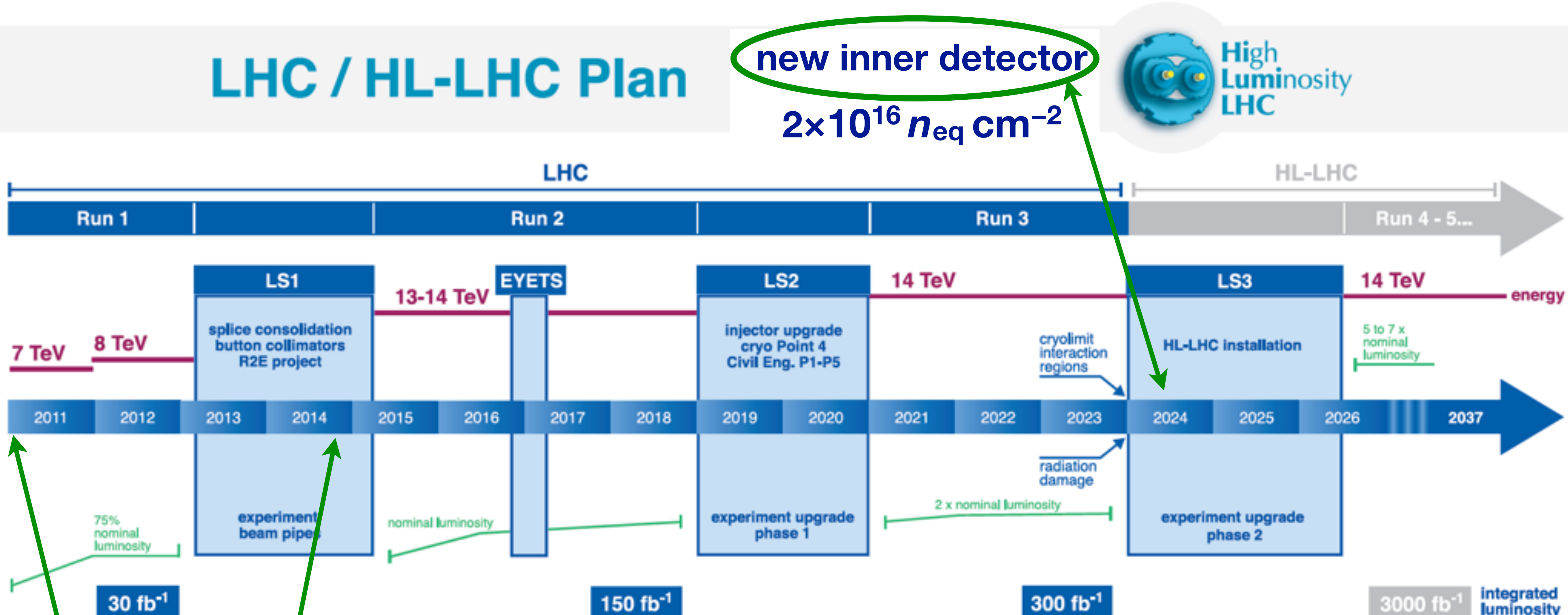


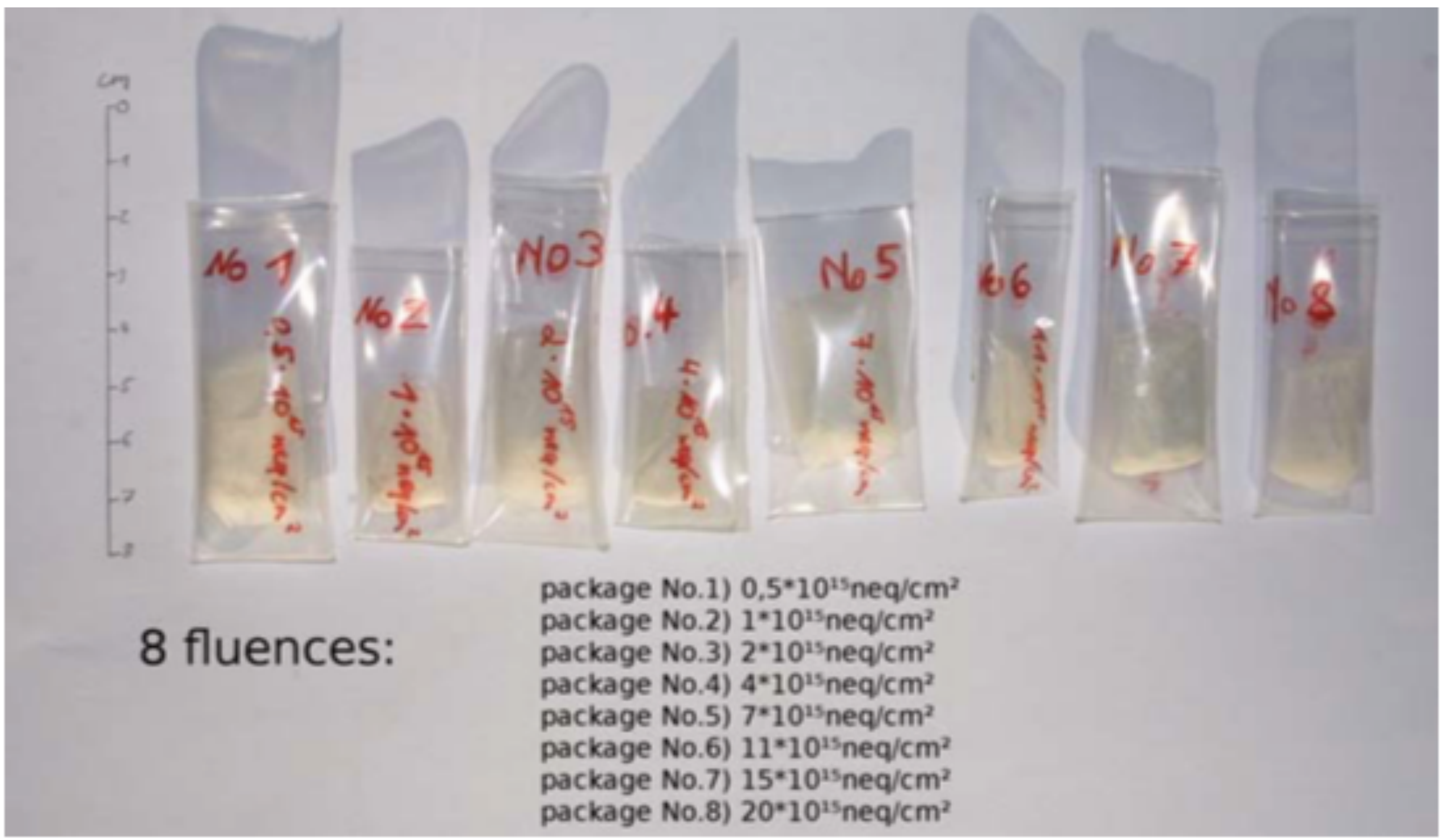


planar n⁺-in-n DOFZ
silicon pixel sensor

3-layer detector: $\mathbf{10^{15}\, n_{eq}\, cm^{-2}}$, FEI-3: 400×50 μm², 250 μm
4th layer (IBL): $\mathbf{5\times10^{15}\, n_{eq}\, cm^{-2}}$, FEI-4: 250×50 μm², 200 μm

Single Chip Sensors & Assemblies and Diodes: Irradiations w/ Reactor Neutrons @ JSI Ljubljana

sensors and diodes have been grouped in bags
to assure similar systematics on irradiation doses



fluences

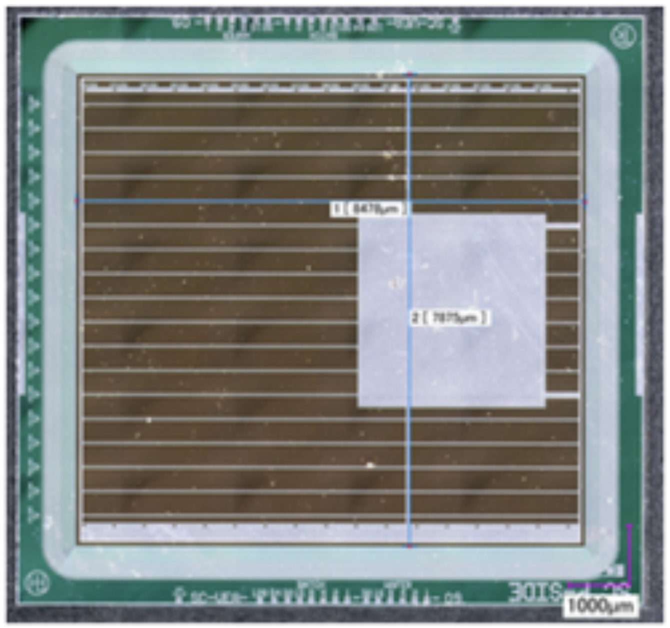
from $0.5 \times 10^{15}\ n_{eq}\,cm^{-2}$
up to $20 \times 10^{15}\ n_{eq}\,cm^{-2}$

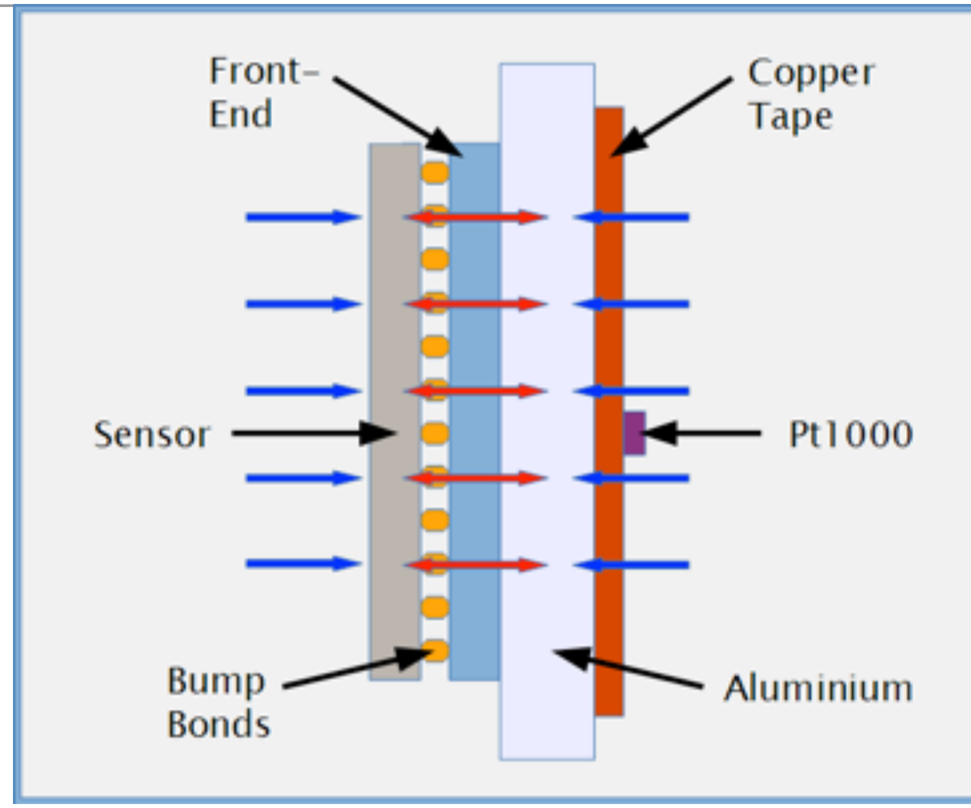
to avoid uncontrolled annealing:

kept sensors continuously
at low temperatures

warm-up limited to short periods
during measurements

FEI-3/FEI-4 Single Chip Sensors & Assemblies
— Cooling and Temperature Monitoring —



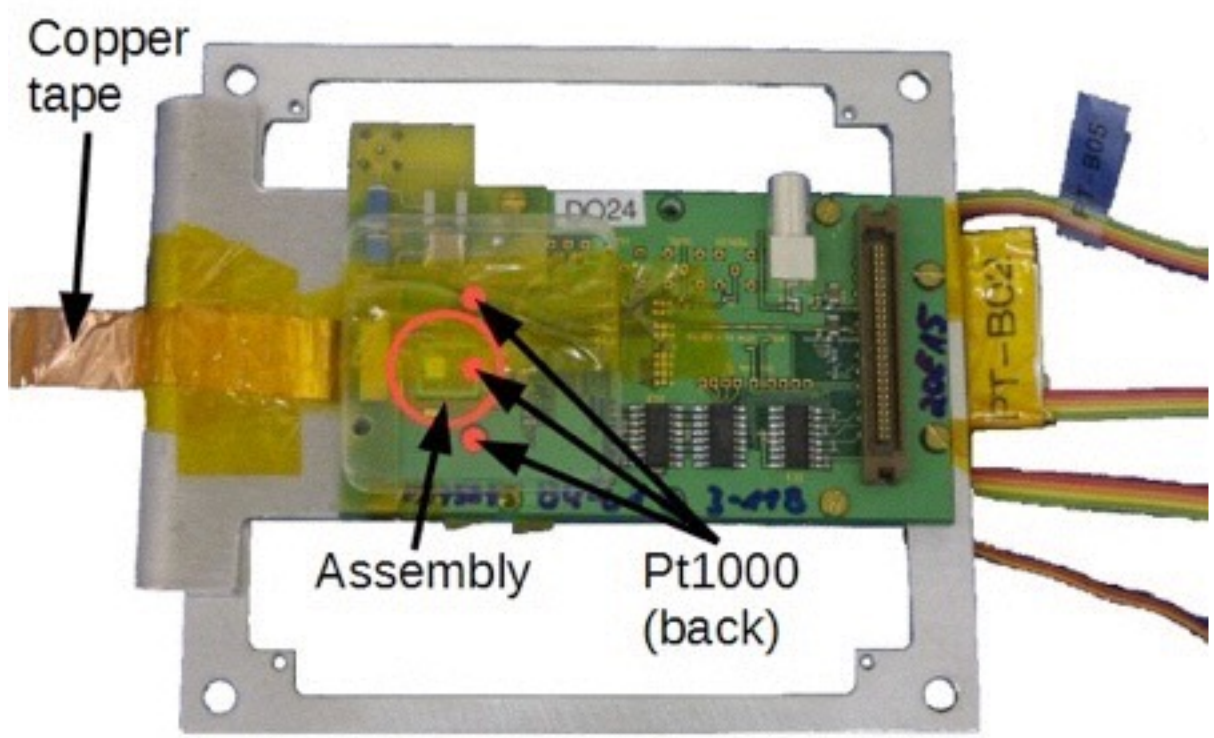


- Pt1000

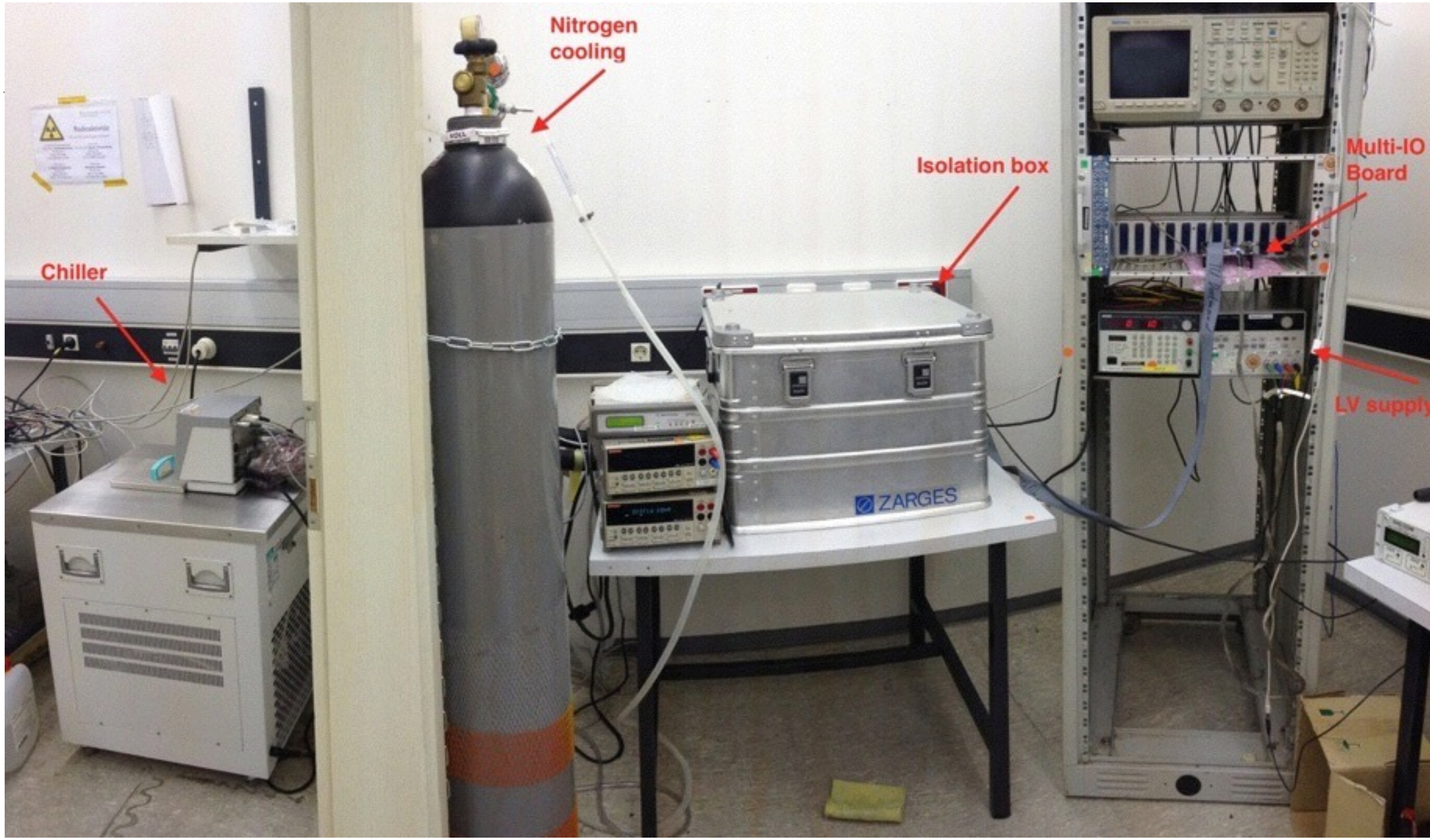
- monitoring of temperature on copper tape on FE-side

- FEs are not operated, nor powered in this study

- cooling of sensors indirectly via copper tape
- attached to cooling plate
- coolant from chiller



View at Lab Set-up



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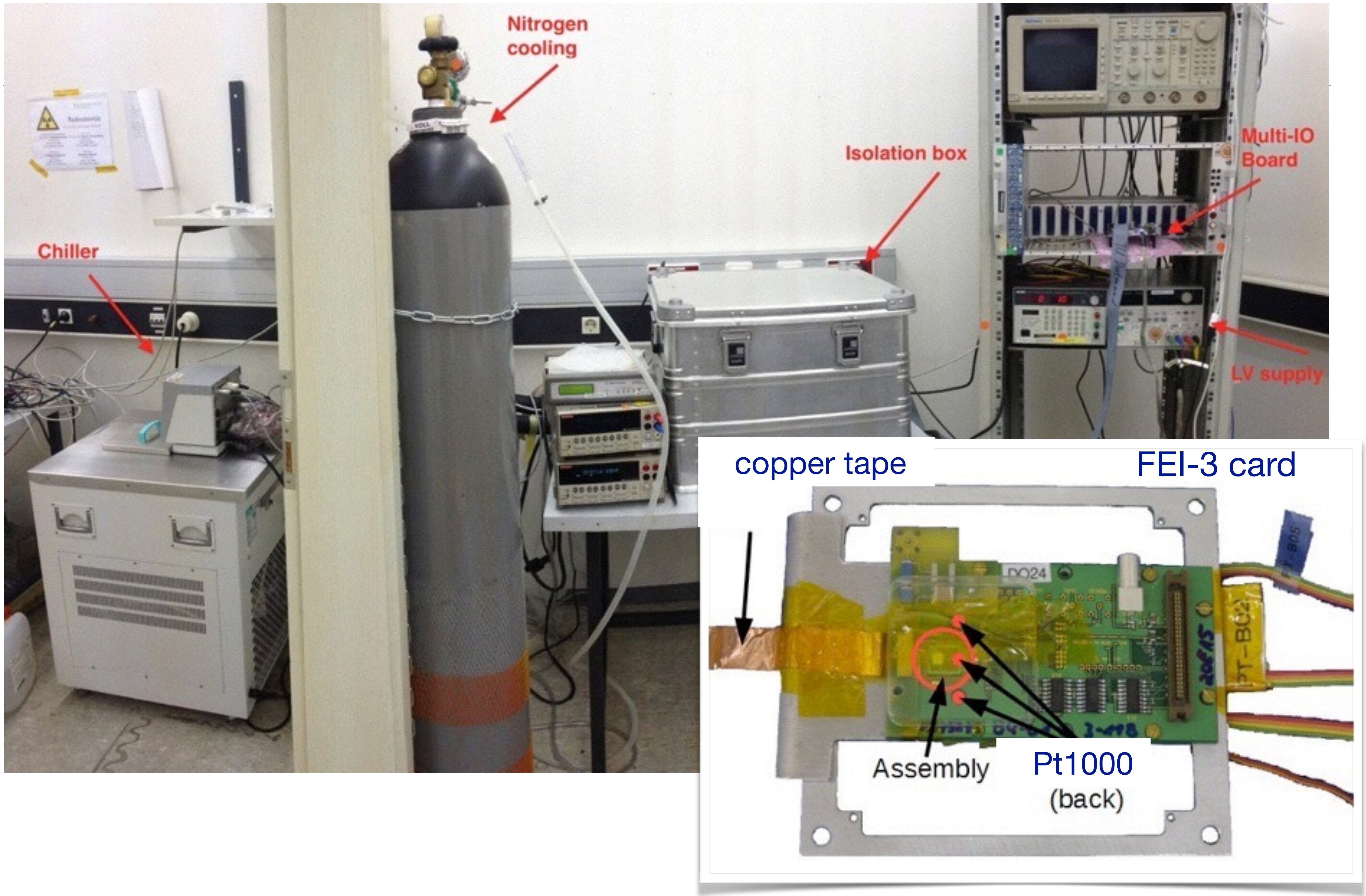
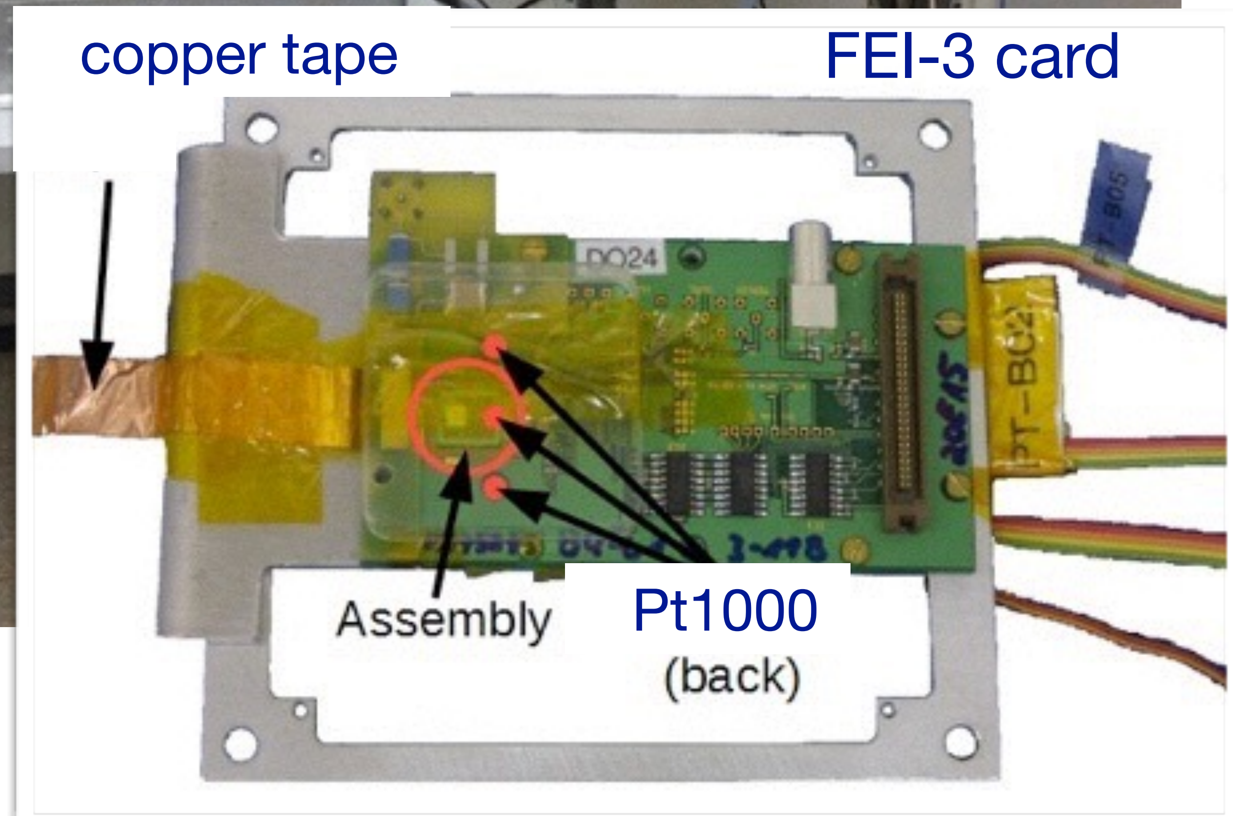


View at Lab Set-up

investigated assemblies:

- n^+-in-n FEI-3 pixel sensors,
  150, 200, 250 µm
  neutron irradiation @ $5\times10^{15}\,n_{eq}\,cm^{-2}$
  i.e. **IBL-like irradiation conditions**
- measurements of leakage currents
  @ different temperatures

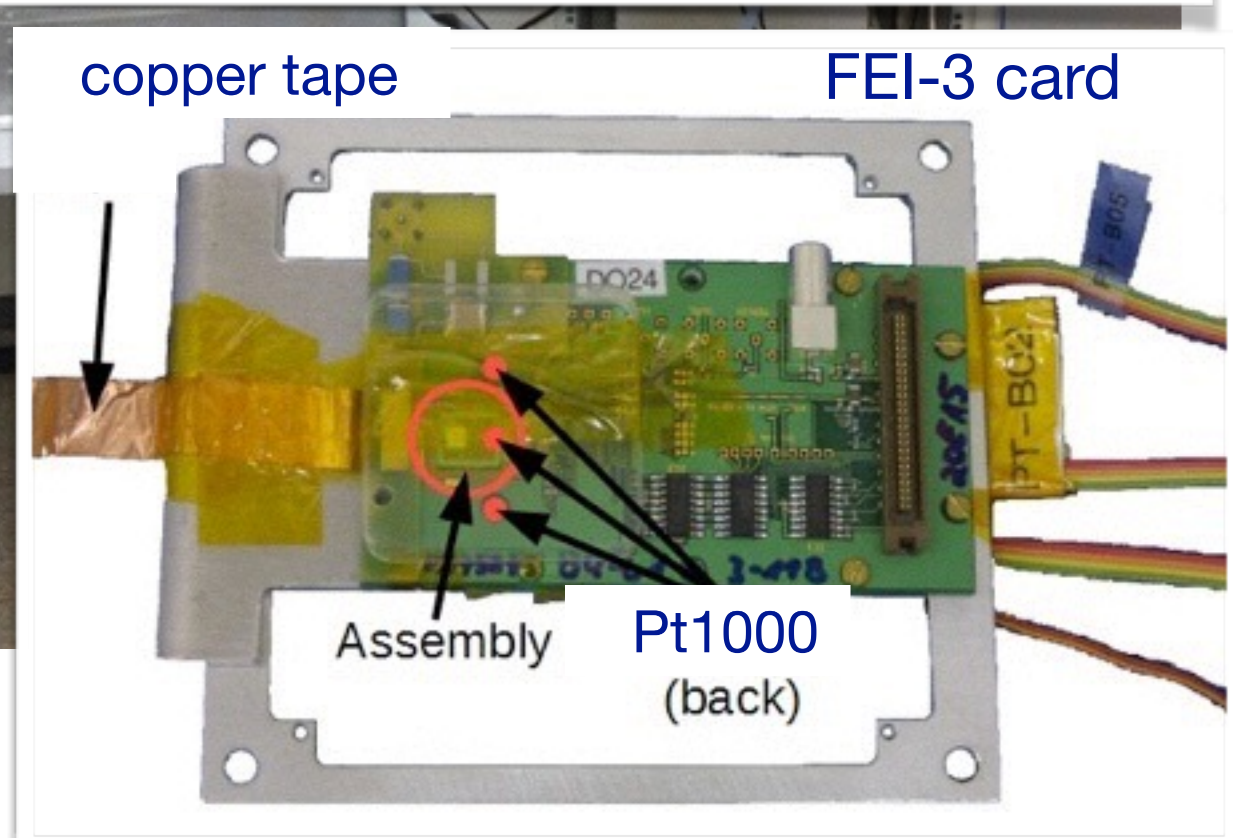


Set of Measurement Data

- IT: leakage current *vs*. temperature @ fixed sensor reverse bias voltage
- IV: leakage current *vs*. reverse bias voltage @ fixed sensor temperature
- ranges: voltages up to 1000 V, temperatures $-40\ °C \leq T \leq -10\ °C$

investigated assemblies:

- n^+-in-n FEI-3 pixel sensors, 150, 200, 250 μm neutron irradiation @ $5\times10^{15}\ n_{eq}\ cm^{-2}$ i.e. **IBL-like irradiation conditions**
- measurements of leakage currents @ different temperatures



Sensor Leakage Current

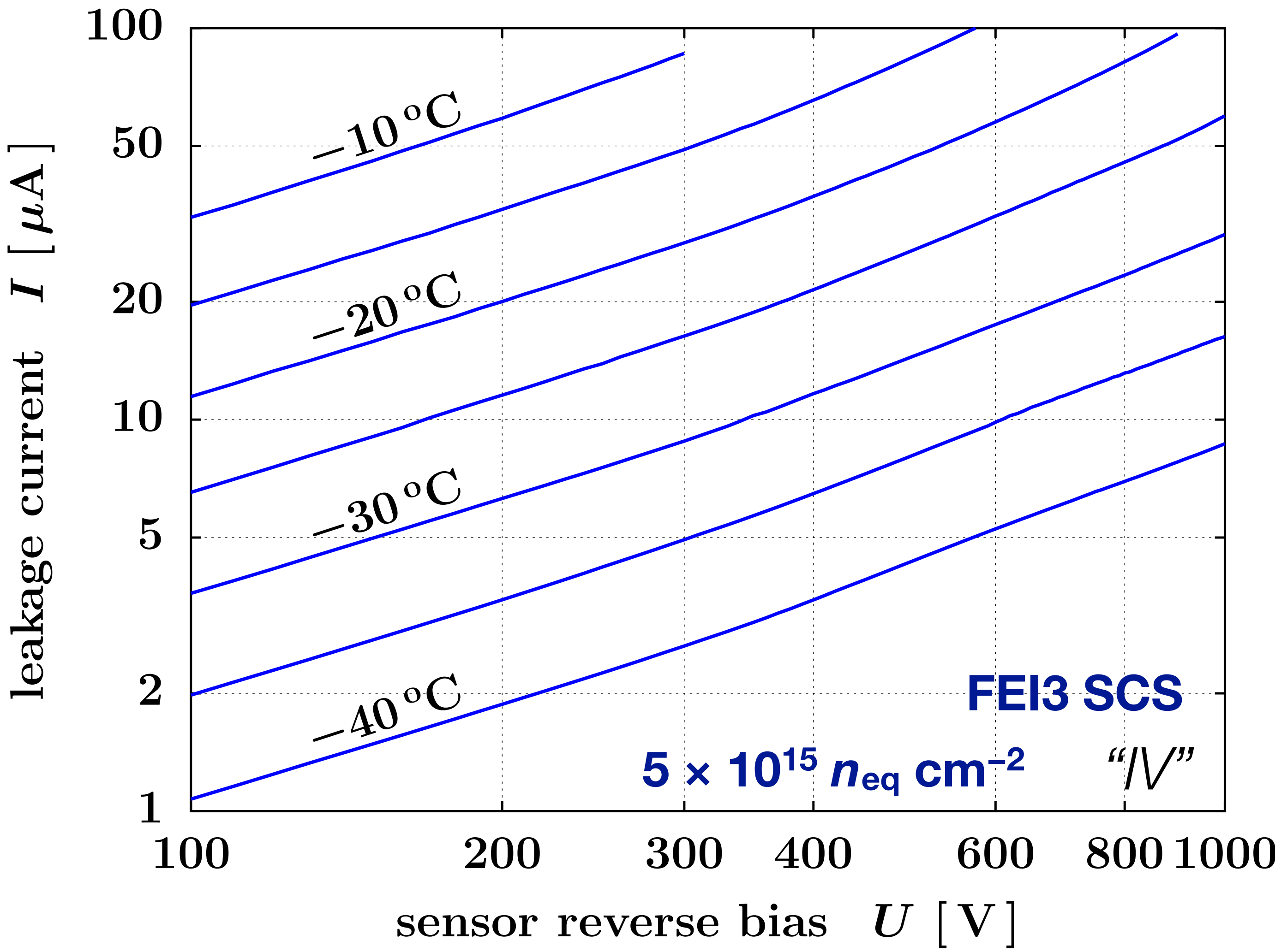
measurements by Carolin Ratering

vs. Voltage @ –40...–10 °C

example of one sample:

$5 \times 10^{15}\, n_{eq}\, cm^{-2}$

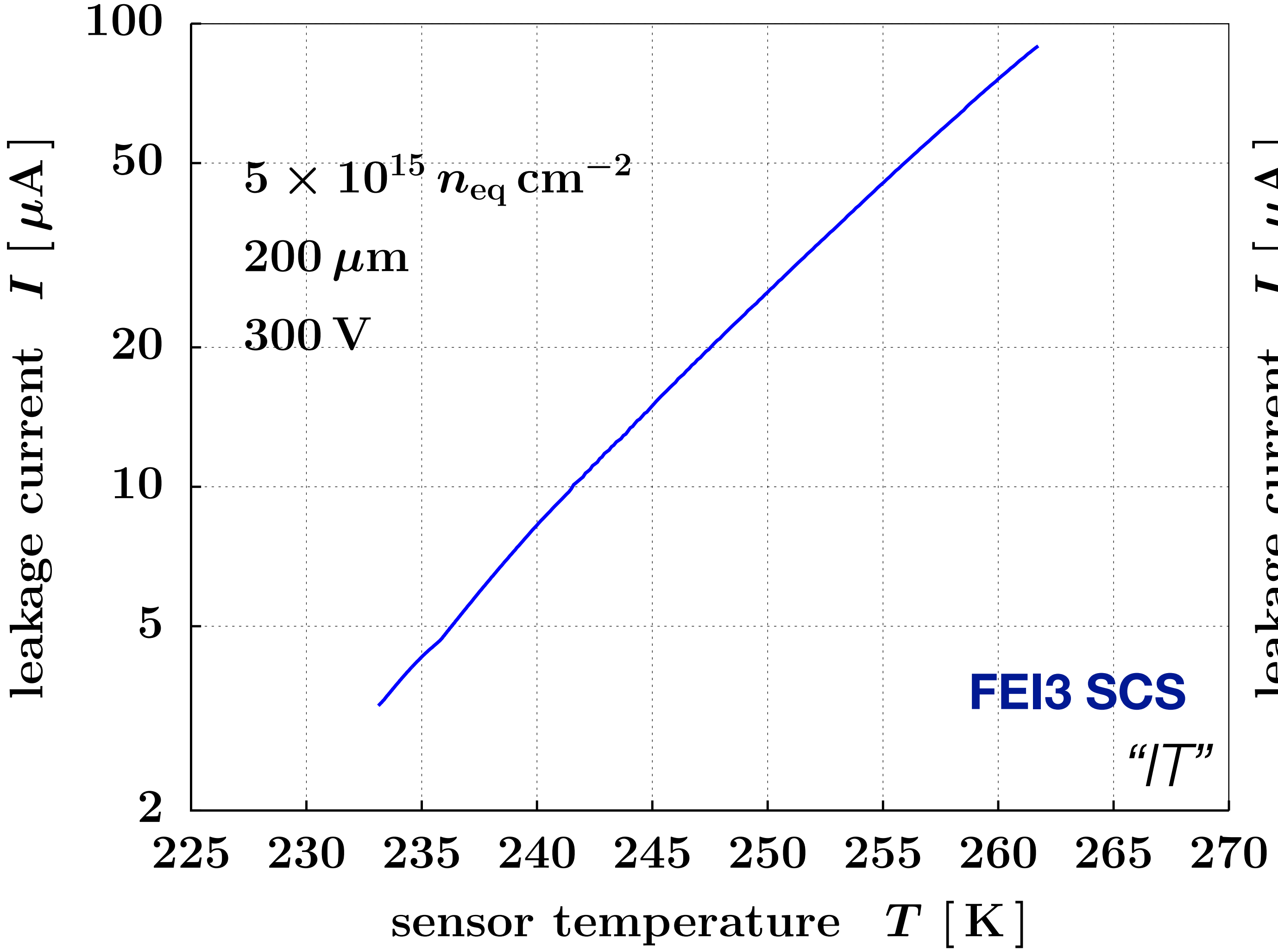
$200\, \mu m$



- measurements of IV characteristics @ various fixed temperatures down to –40 °C *measurements by Carolin Ratering*

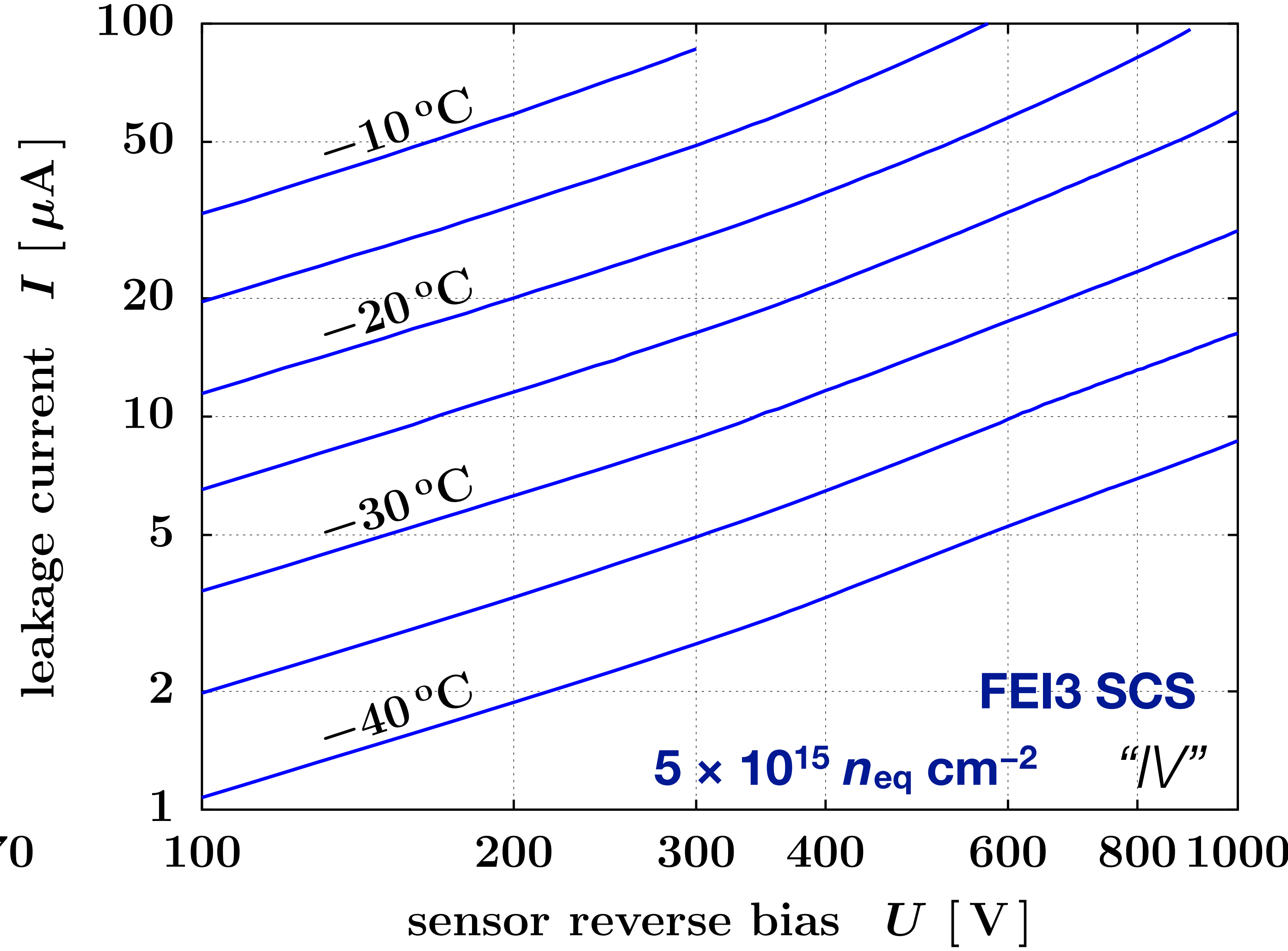
Sensor Leakage Current

vs. Temperature @ 300 V



- measurements of leakage current *vs*. temperature @ fixed bias voltage

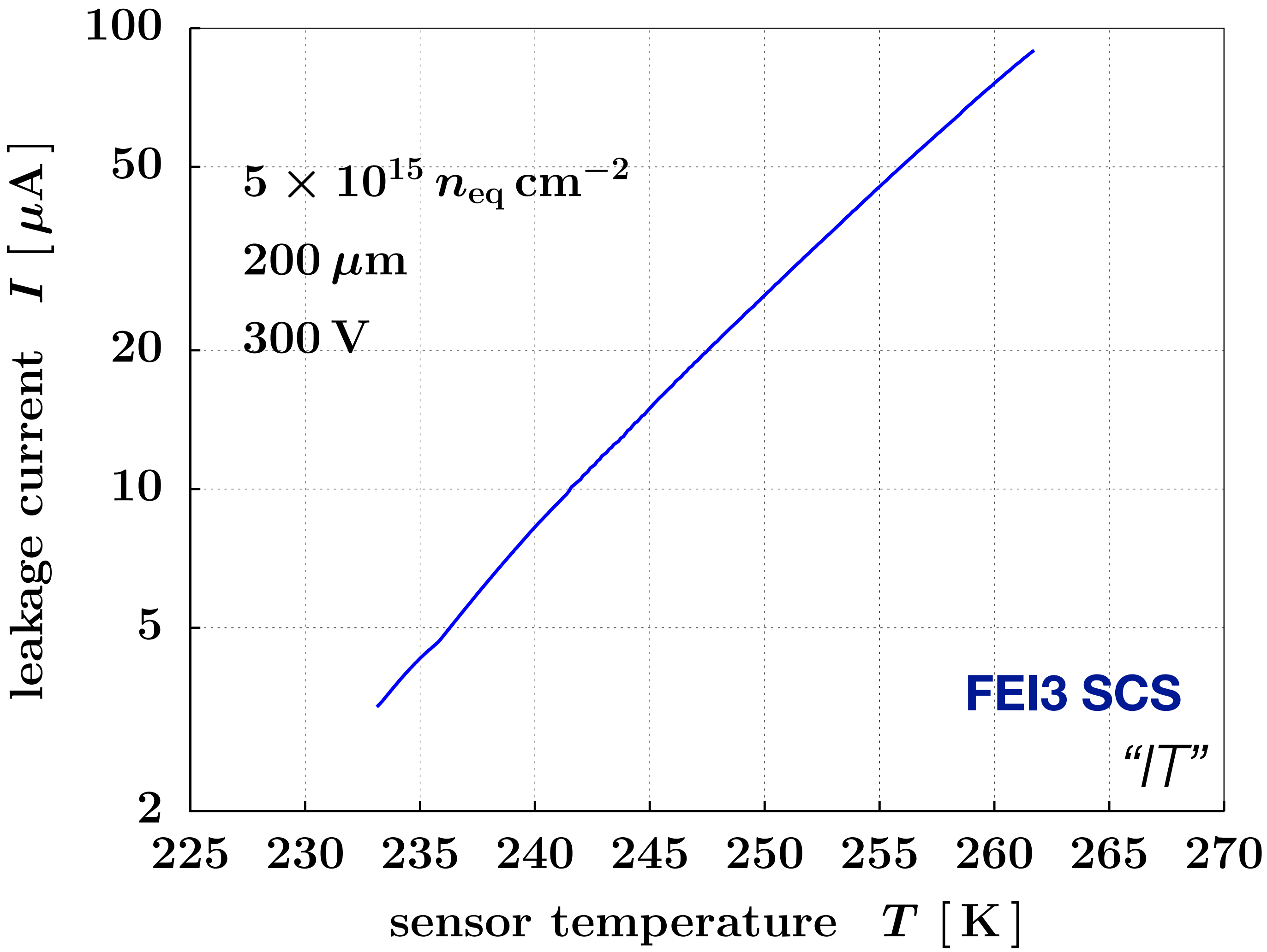
vs. Voltage @ –40…–10 °C



- measurements of IV characteristics @ various fixed temperatures down to –40 °C

method published in:
*NIM A **765** (2014) 135-139*

Sensor Leakage Current *vs*. Temperature @ 300 V



- measurements of leakage current *vs*. temperature @ fixed bias voltage

steps to extract current scaling:

use IT data @ fixed bias voltage to determine the scaling of currents with temperature:

- assume $I = A \cdot T^2 \exp - \frac{E_{g,eff}}{2kT}$
- write as 1st order polynomial $p_1(T)$

$$-2kT \cdot \ln \frac{I}{T^2} = p_1(T) = B - \ln(A) \cdot 2kT$$

to determine normalization A

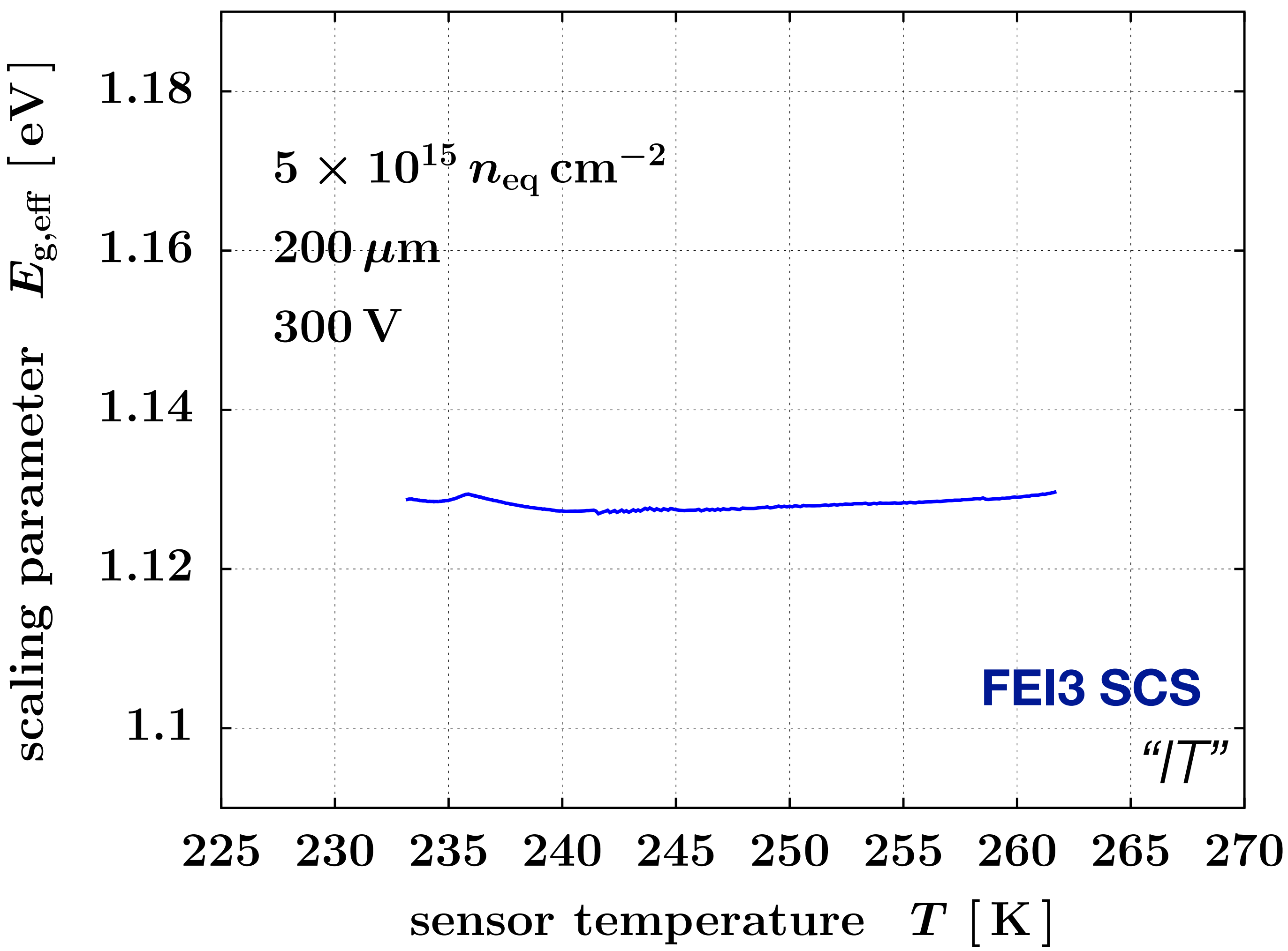
- re-calculate data as $E_{g,eff}$

$$E_{g,eff}(T) = -2kT \cdot \ln \frac{I}{A \cdot T^2}$$

to determine leakage current scaling parameter

Leakage Current Scaling Parameter *vs*. Temperature @ 300 V

method published in:
*NIM A **765** (2014) 135-139*



- observe allmost constant scaling parameters with temperature
- some deviations at low temperature

steps to extract current scaling:

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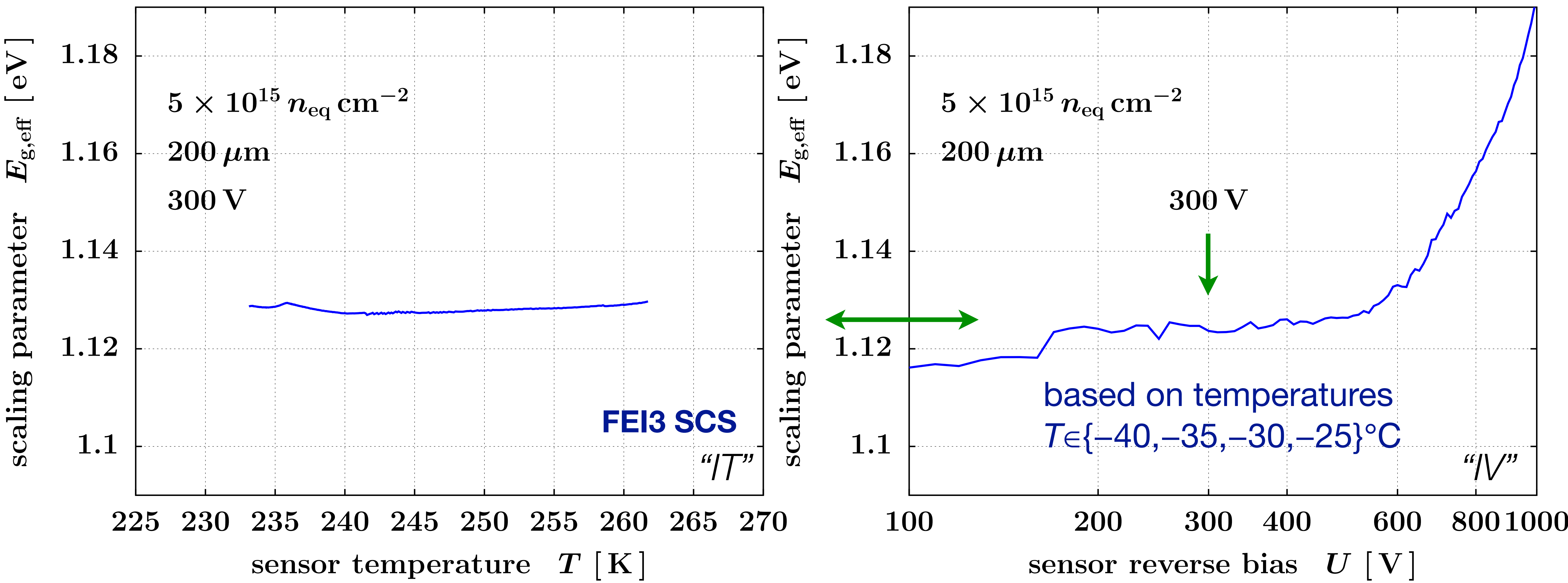
$$E_{g,eff}(T) = -2kT \cdot \ln \frac{I}{A \cdot T^2}$$

to determine leakage current scaling parameter

Leakage Current Scaling Parameter

vs. Temperature @ 300 V   *vs*. Bias Voltage

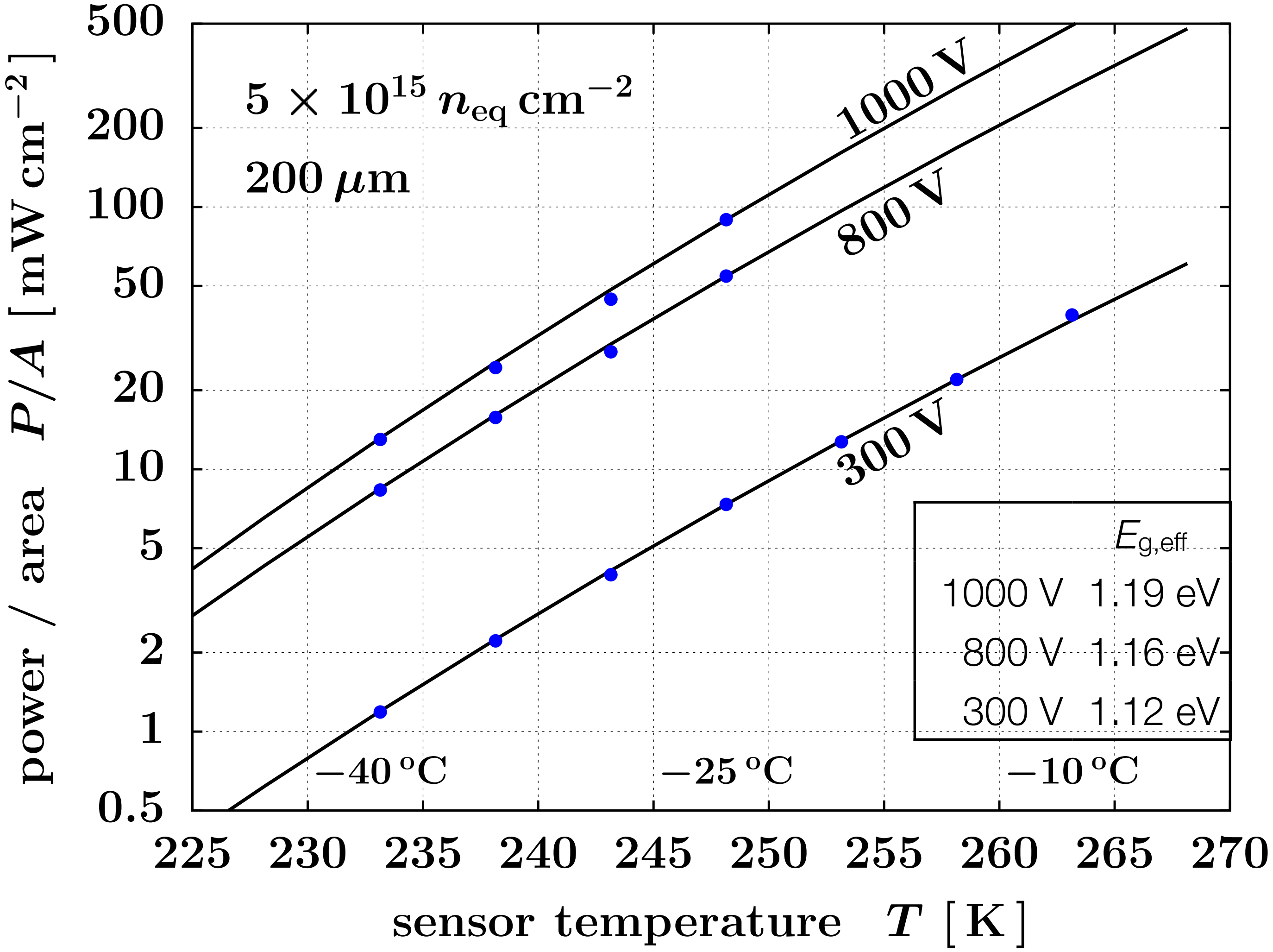


- observe allmost constant scaling parameters with temperature
- some deviations at low temperature

- repeat the exercise for IV data
- determine individual leakage current scaling parameters as a function of the sensor bias voltage

*measurements by
Carolin Ratering*

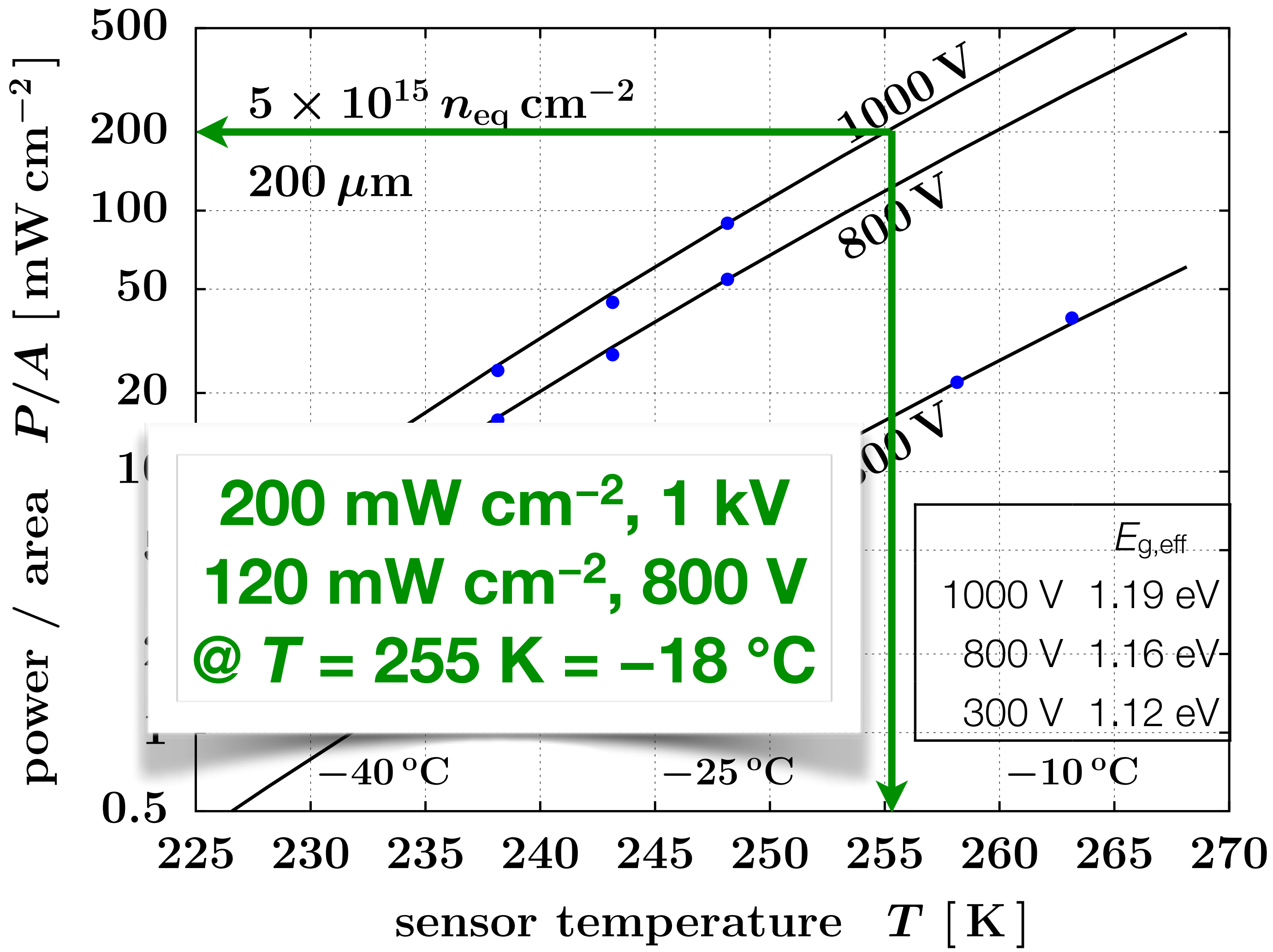
Power Dissipation *vs*. Temperature



- apply temperature scaling to leakage currents to interpolate & extrapolate power dissipations in a wide temperature range

Power Dissipation *vs*. Temperature

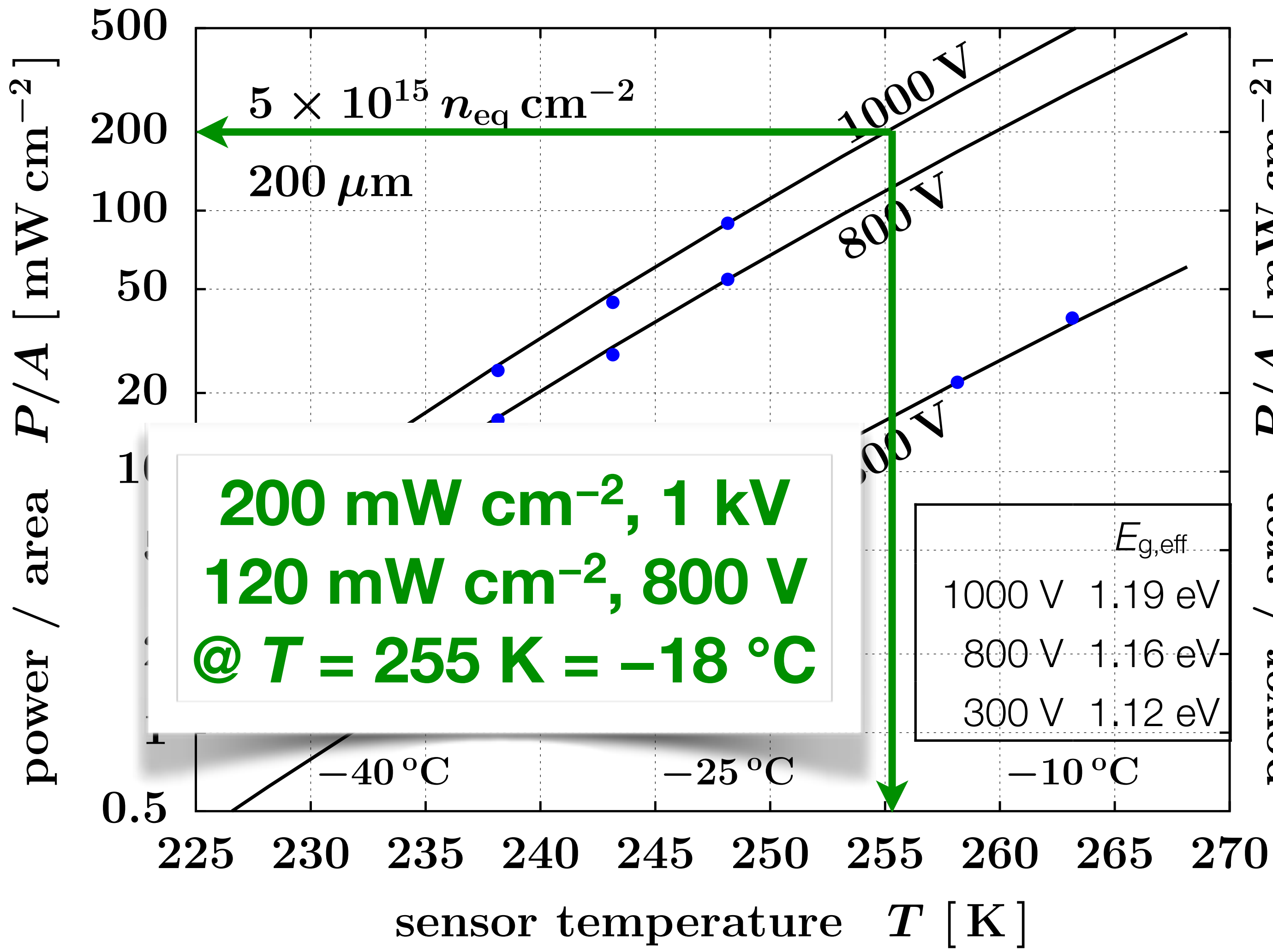
measurements by Carolin Ratering

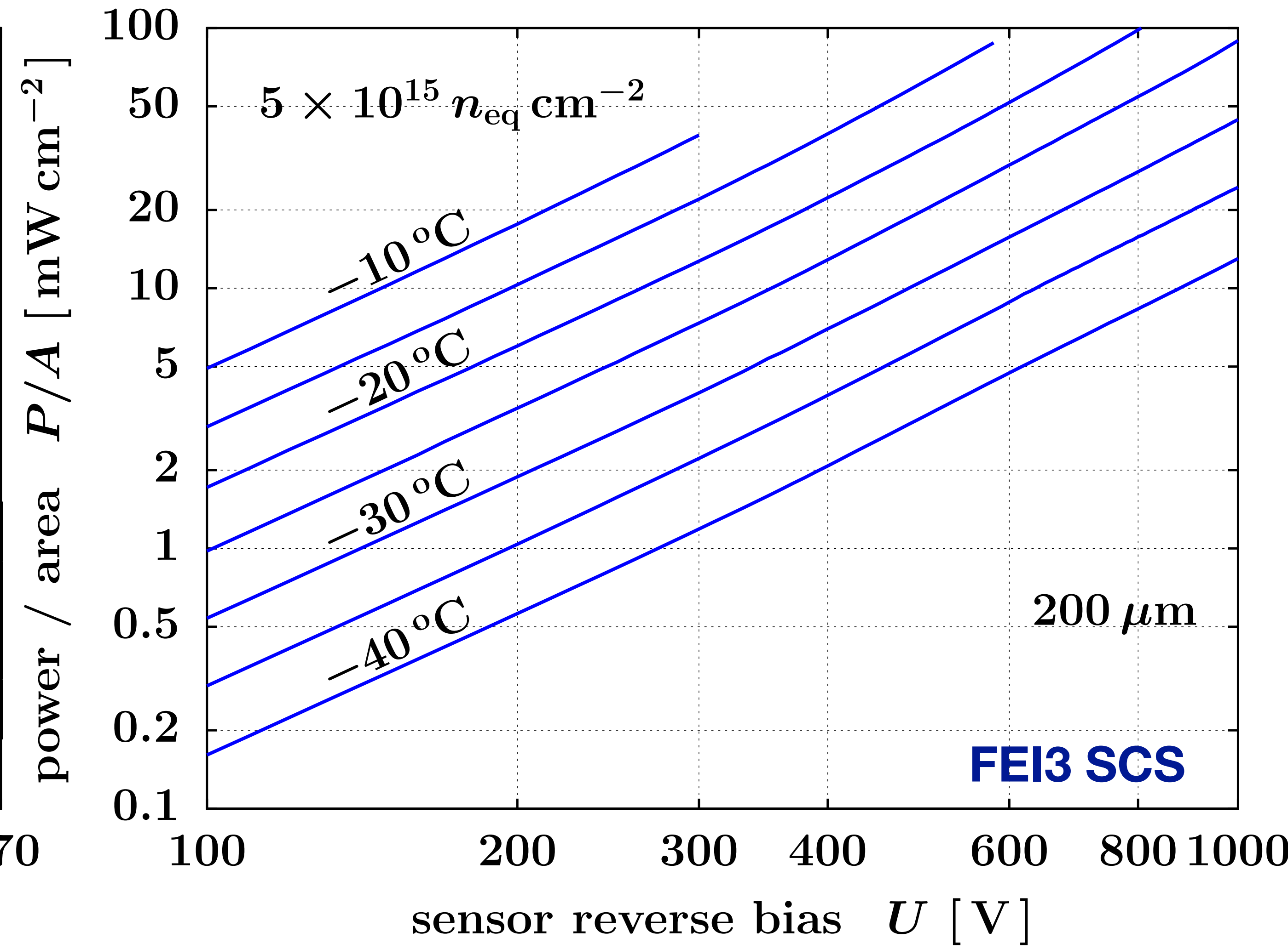


- apply temperature scaling to leakage currents to interpolate & extrapolate power dissipations in a wide temperature range

measurements by
Carolin Ratering

Power Dissipation
vs. Temperature   *vs*. Voltage @ –40...–10 °C



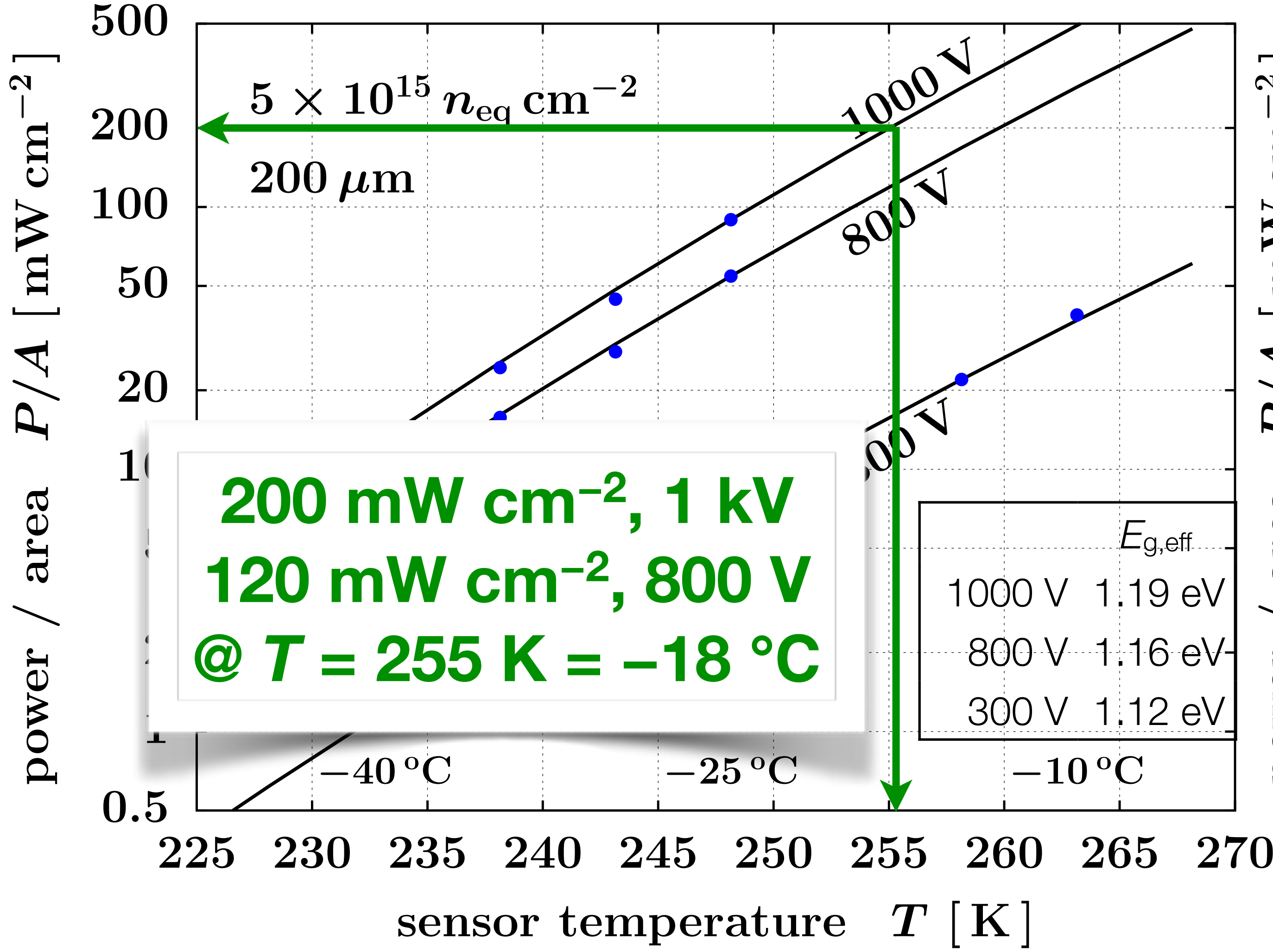


- apply temperature scaling
  to leakage currents
  to interpolate & extrapolate
  power dissipations
  in a wide temperature range

- determine power dissipations
  as a function of the bias voltage

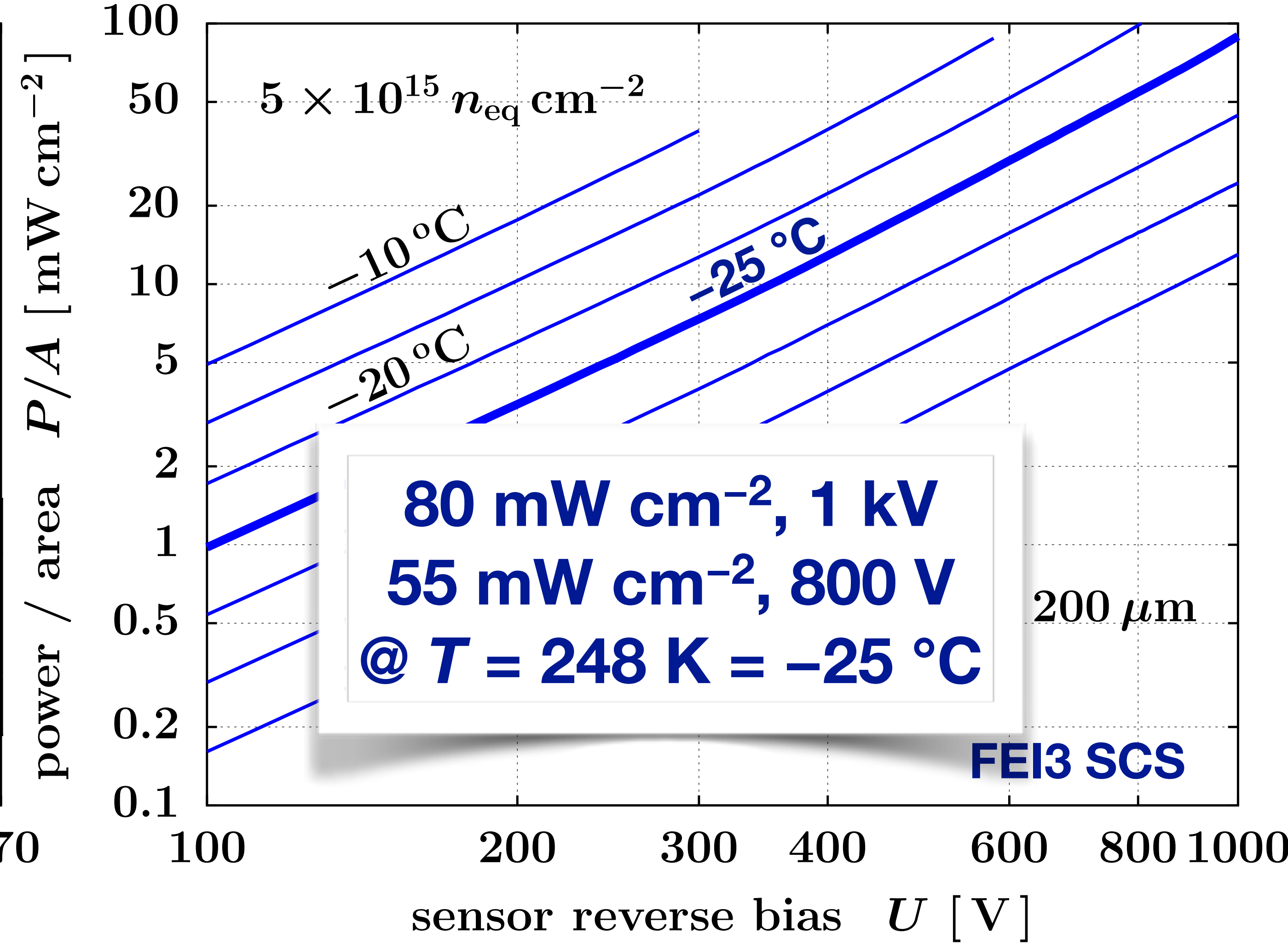
measurements by Carolin Ratering

Power Dissipation *vs*. Temperature



- apply temperature scaling to leakage currents to interpolate & extrapolate power dissipations in a wide temperature range

vs. Voltage @ –40...–10 °C



- determine power dissipations as a function of the bias voltage

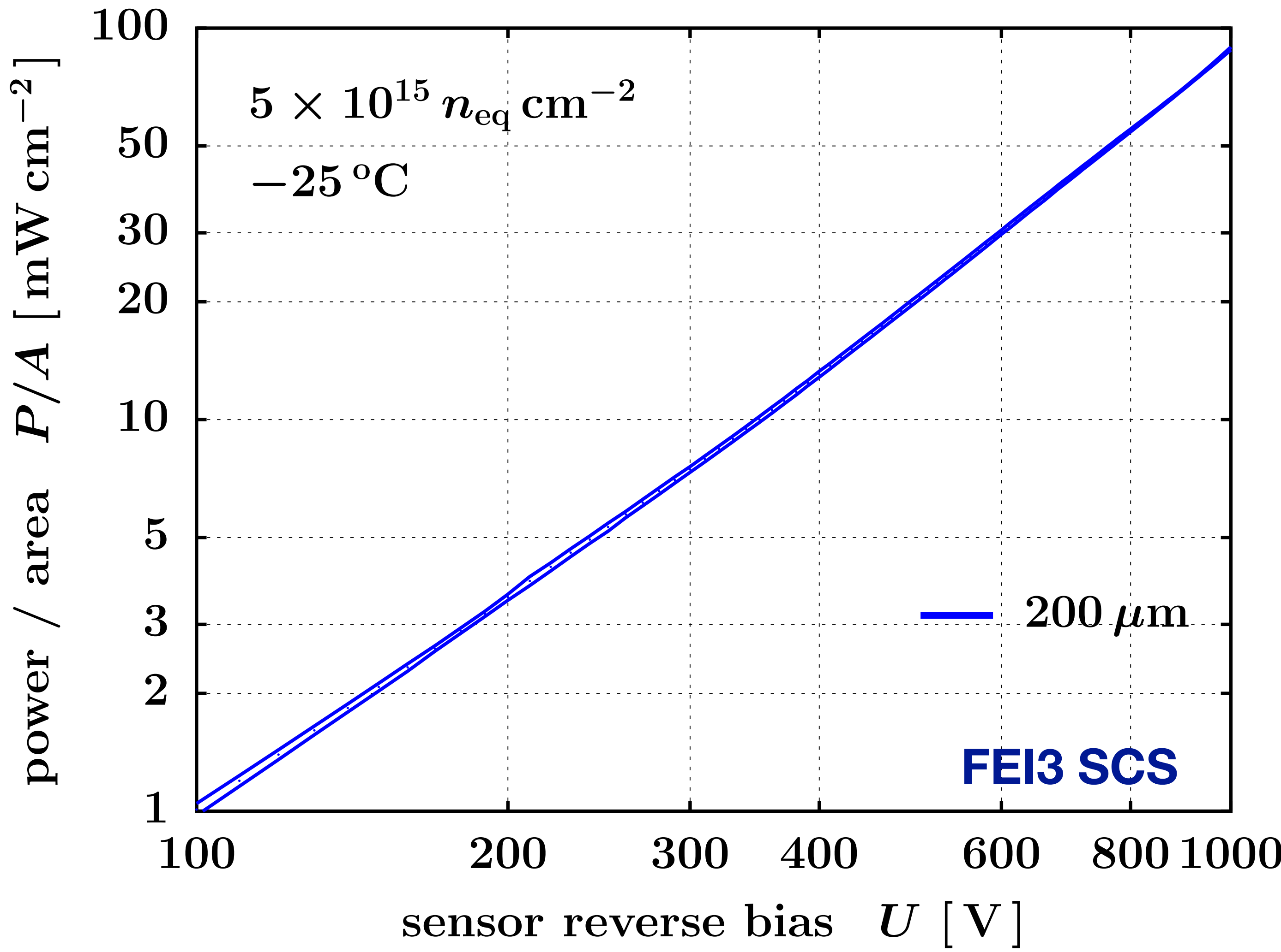
Power Dissipation

measurements by Carolin Ratering

@ 200 µm

repeat study

including more samples



- closer look to values at one fixed temperature of –25 °C

Power Dissipation

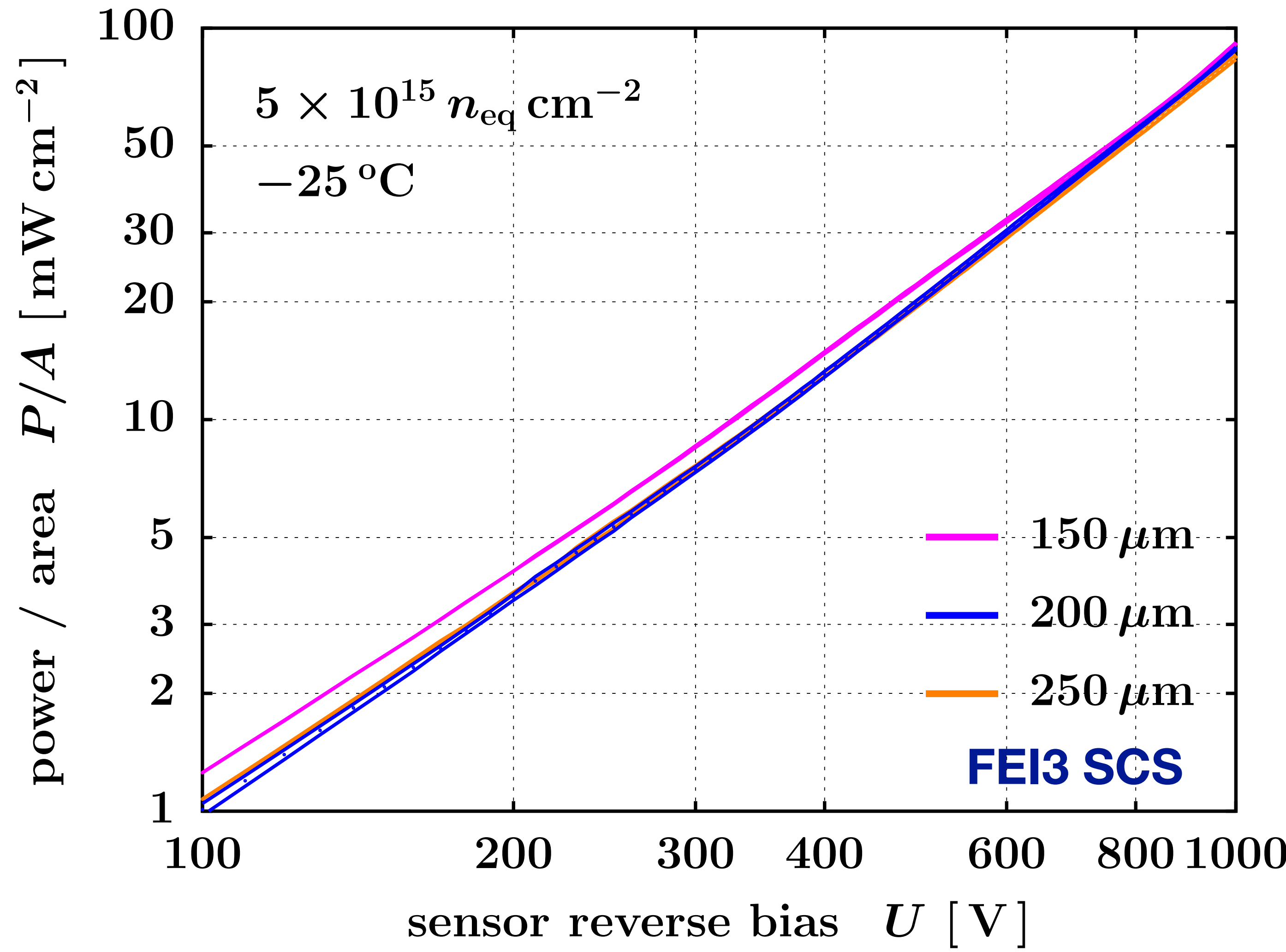
measurements by Carolin Ratering

@ 200 µm *vs*. 150 & 250 µm

repeat study

including more samples

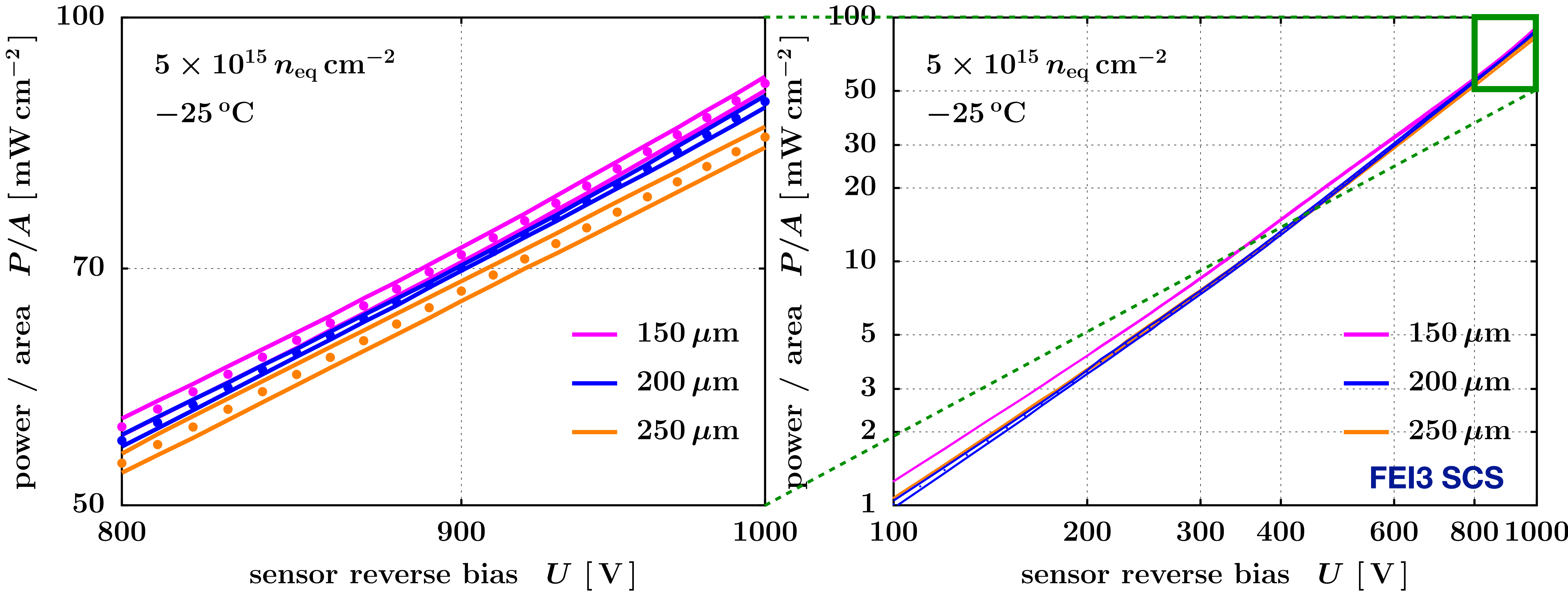
& different thicknesses



- closer look to values at one fixed temperature of –25 °C
- sensors with different thicknesses look similar — with a slight systematics?

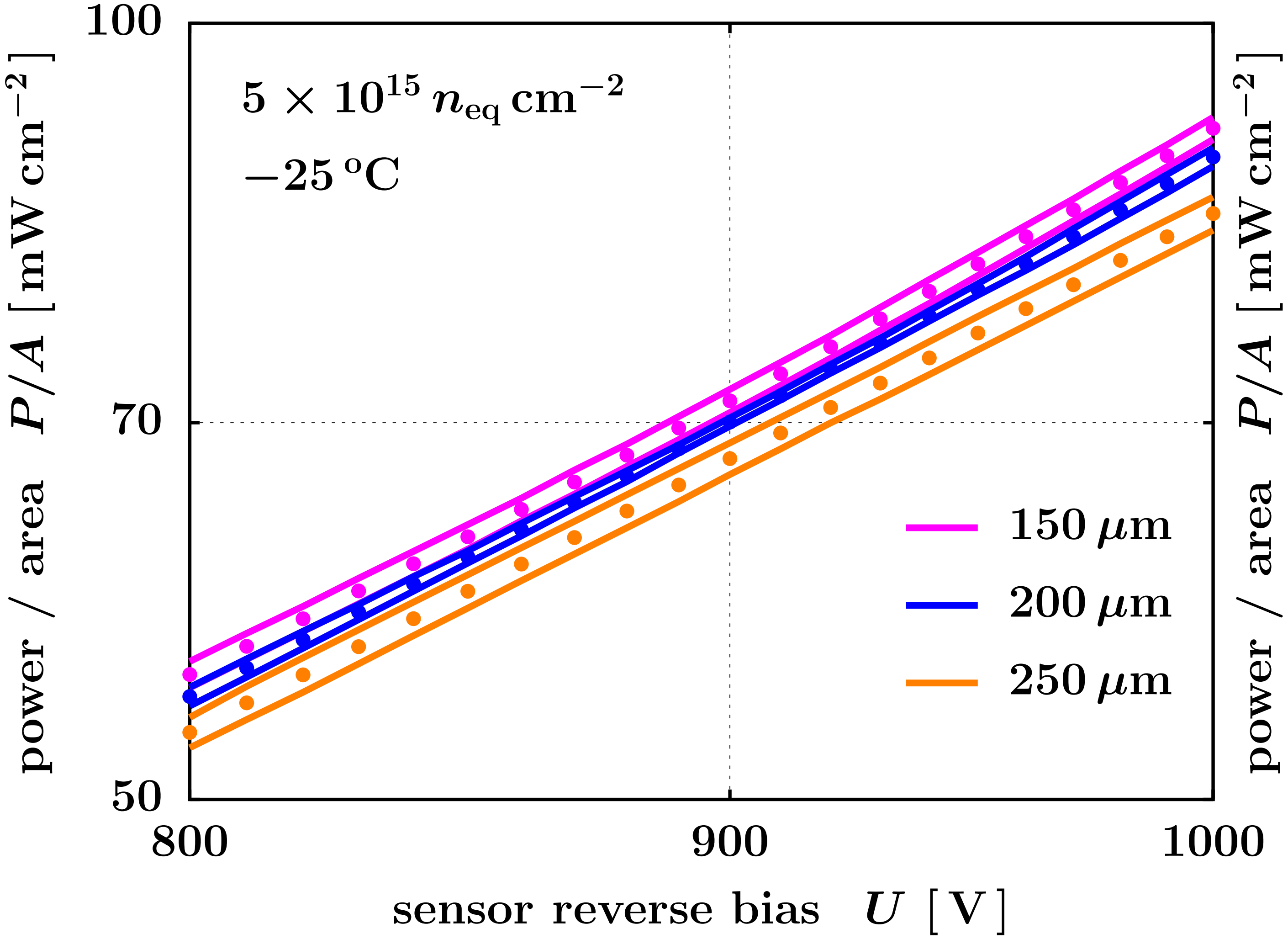
Power Dissipation zoomed into high voltages @ 200 µm *vs*. 150 & 250 µm

measurements by Carolin Ratering

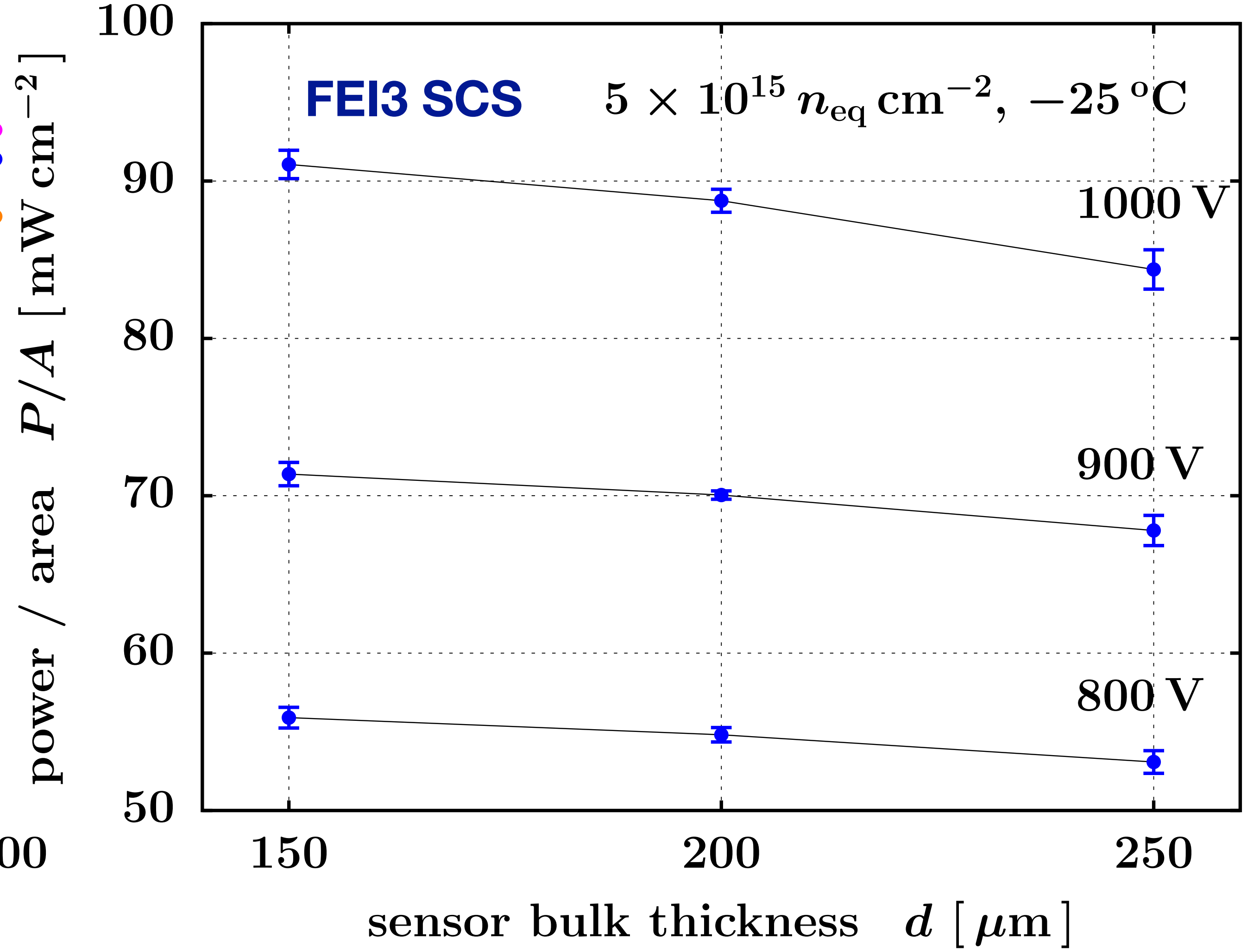


- closer look to values at one fixed temperature of –25 °C
- sensors with different thicknesses look similar — with a slight systematics?
- focus on high voltages

Power Dissipation zoomed into high voltages



Power Dissipation *vs*. thickness



- a slight decrease of power dissipation with increasing bulk thickness is observed
- thicker sensitive volume in thinner sensor?

cross-check with hit efficiency measurements

Power Dissipation *vs*. thickness

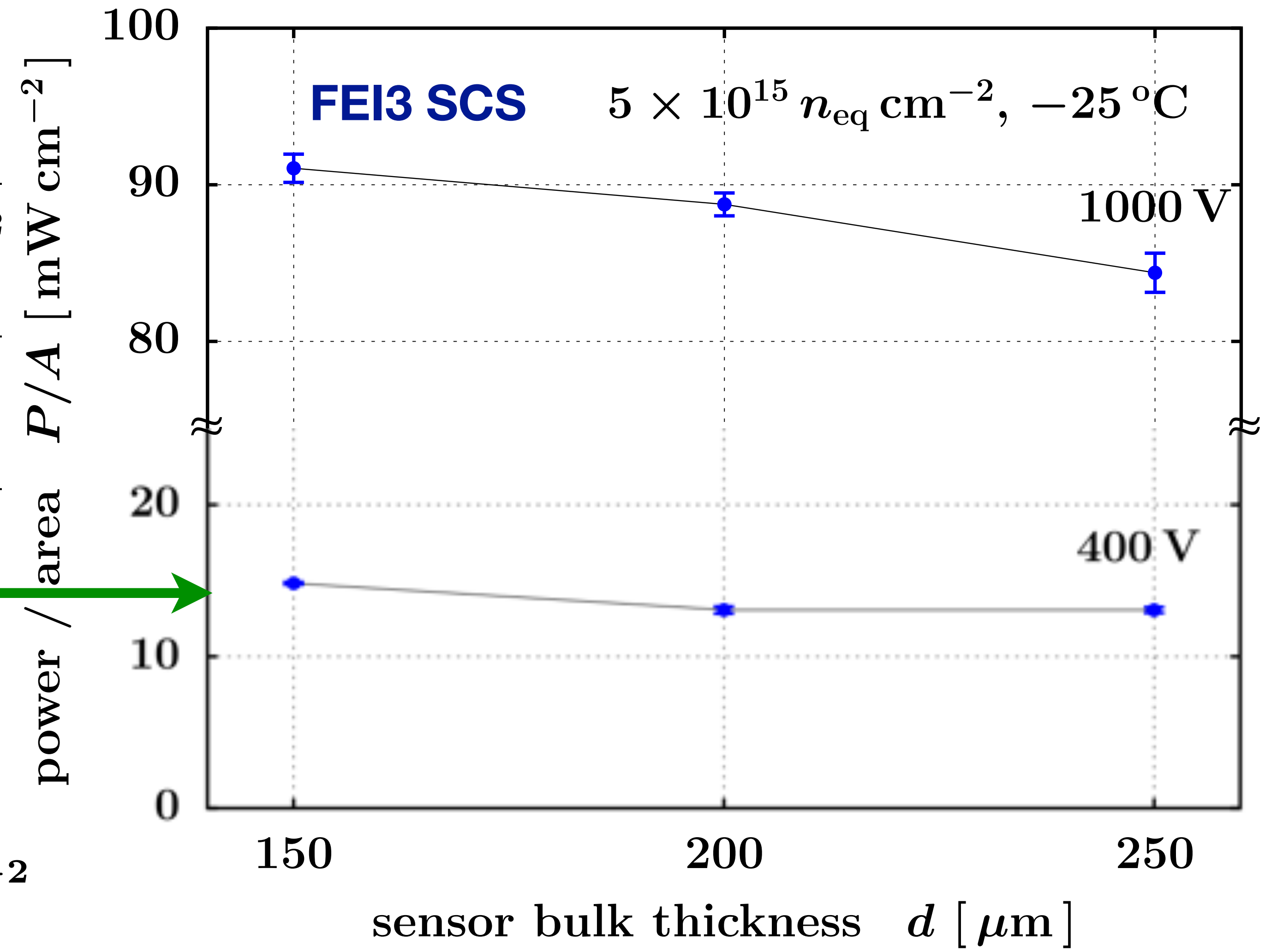
[1] *Tobias Wittig, PhD thesis 2013*
[2] *Silke Altenheiner, PhD thesis 2015*

thickness	150	250	μm
fluence	5×10^{15}	4×10^{15}	$n_{eq}\,cm^{-2}$
bias	400	400	V
front-end	FEI-3	FEI-4	
threshold	3200	1600	e
hit efficiency	97 [1]	95 [2] / 90 [1]	%

same bias conditions

same hit efficiency of 97%

bias	400	600 / 800	V
power	15	35 / 55	$mW\,cm^{-2}$



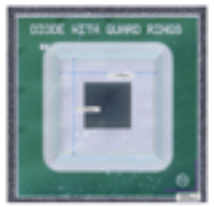
- thinner sensors show higher hit efficiency

  → consistent picture

- a slight decrease of power dissipation with increasing bulk thickness is observed
- thicker sensitive volume in thinner sensor?

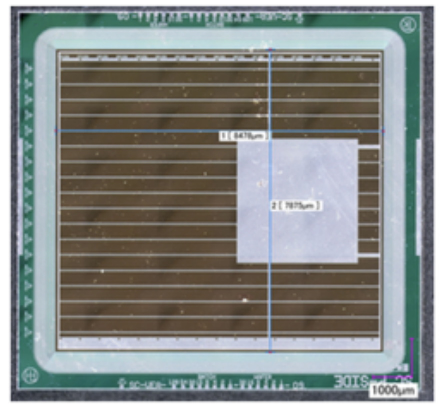
Leakage Current Area Densities *vs*. Sensor Area, non-irradiated

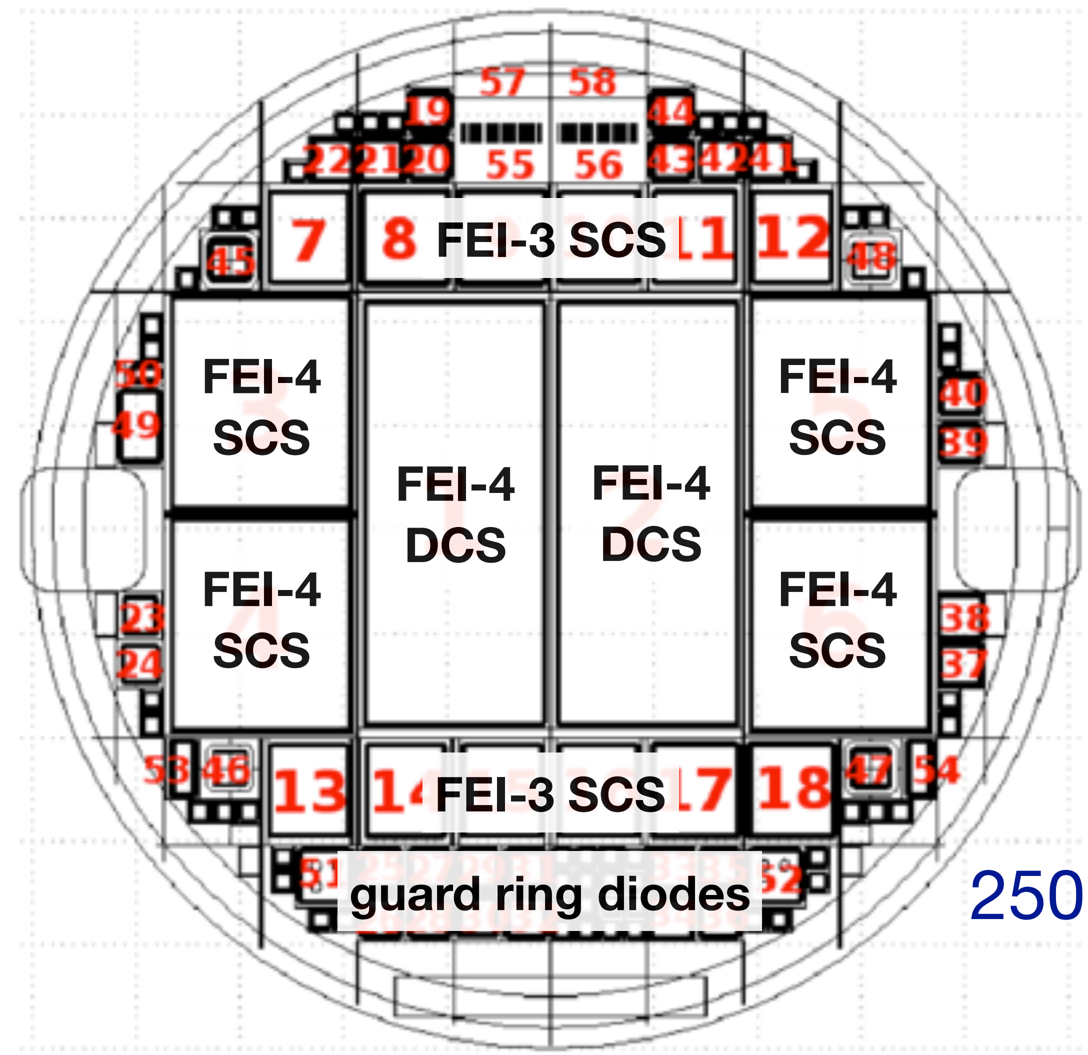
ATLAS phase 0 upgrade
IBL prototype wafer 2010



guard ring diodes ~10 mm^2

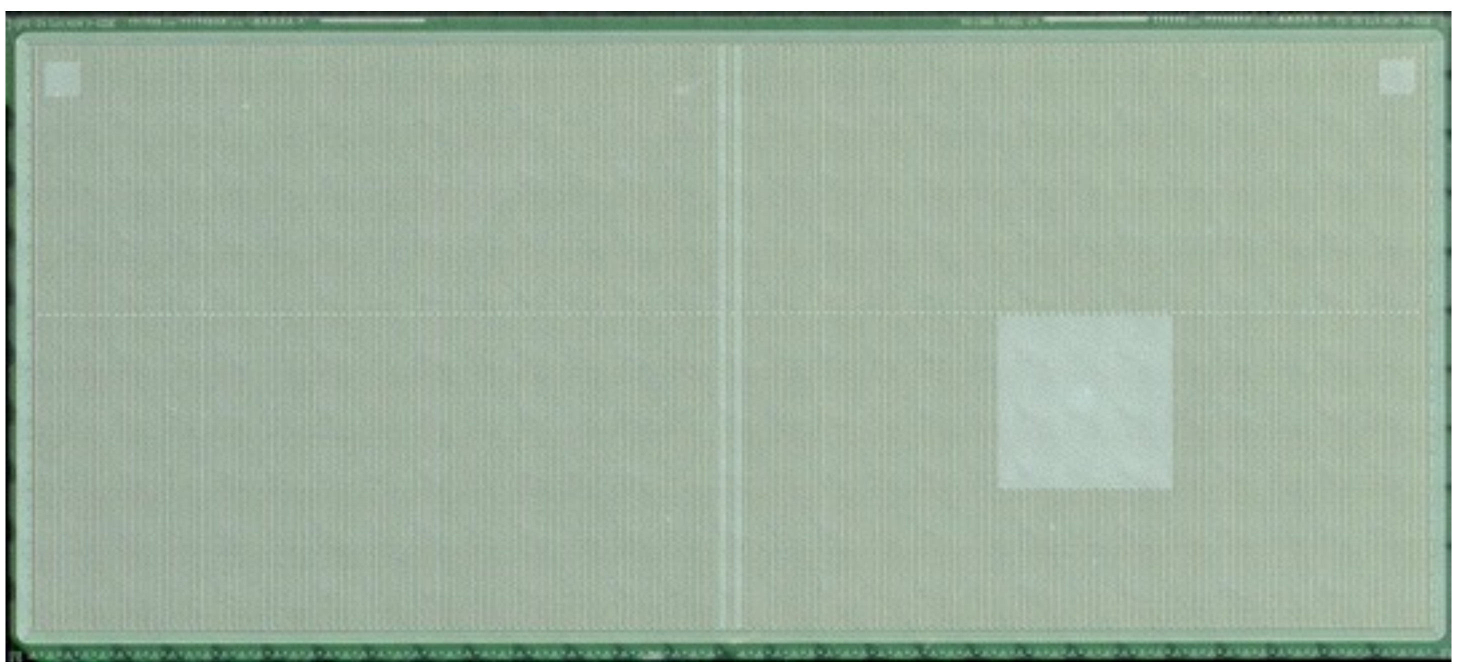
FEI-3 single chip sensors, ~70 mm^2





design by Tobias Wittig

FEI-4 single & double chip sensors, ~350 mm^2 *vs.* ~700 mm^2



250 µm

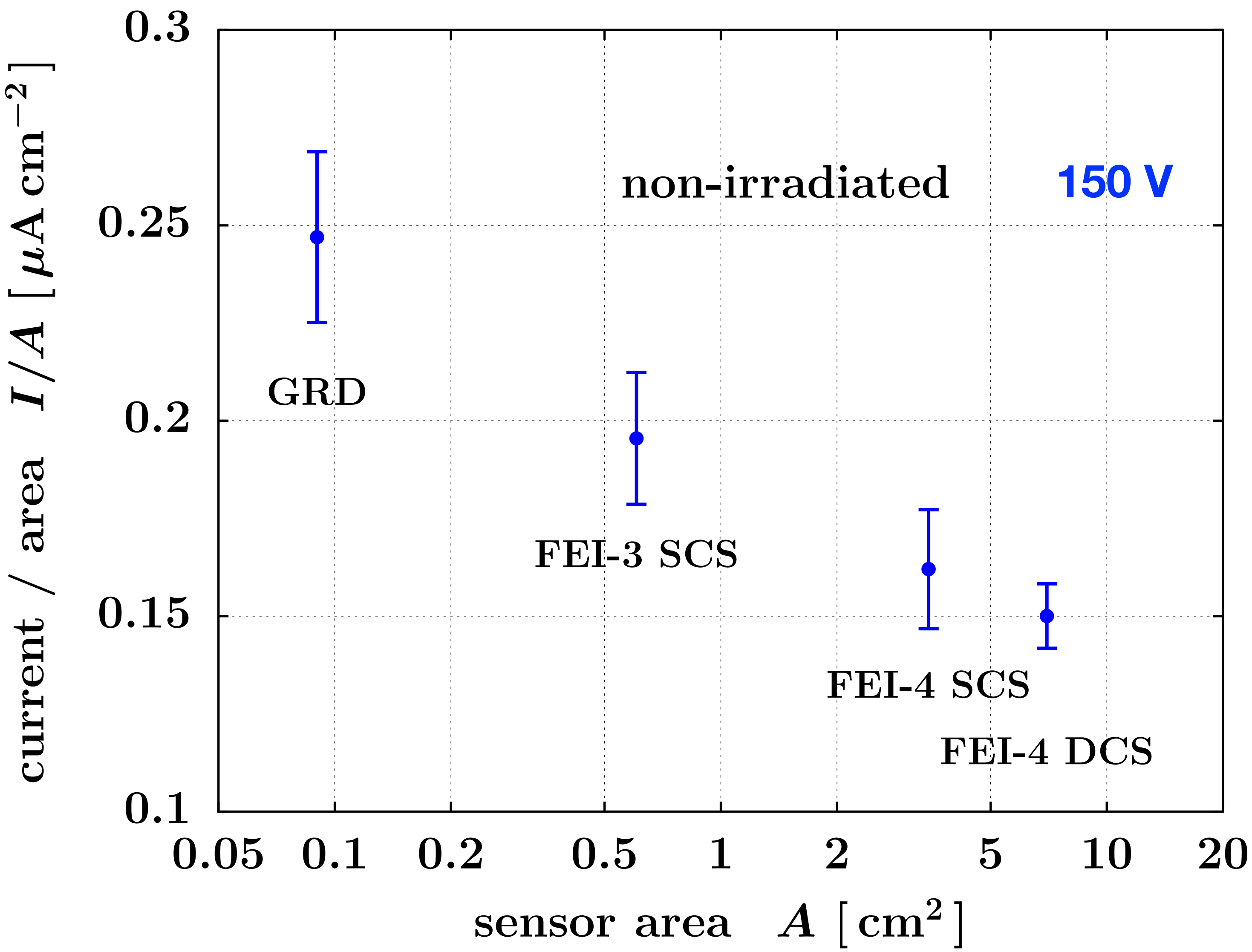
similar FEI-4 DCS used for IBL

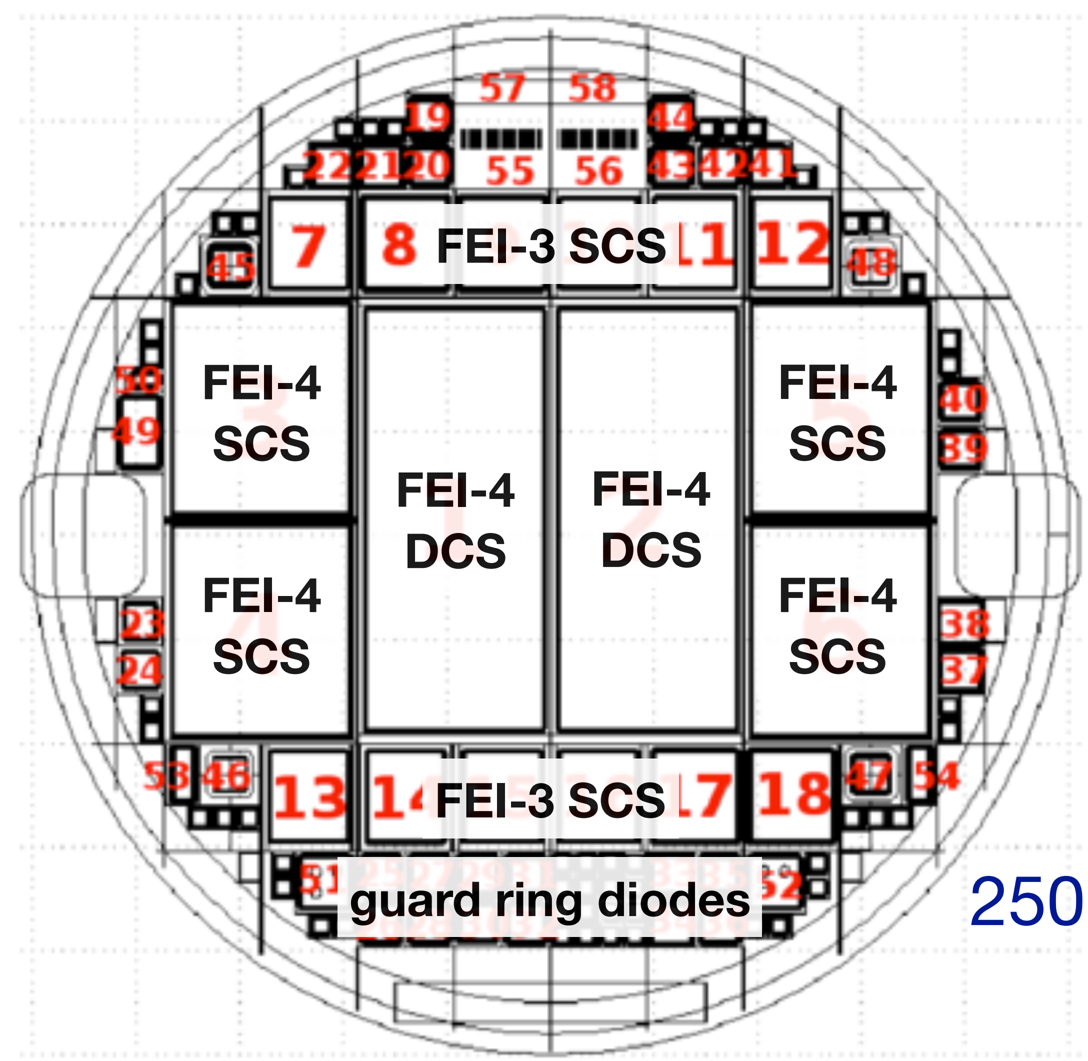
- measurements were carried out on a non-diced, non-irradiated wafer

measurements by
Daniel Bryan

Leakage Current Area Densities *vs*. Sensor Area, non-irradiated

ATLAS phase 0 upgrade
IBL prototype wafer 2010





design by Tobias Wittig

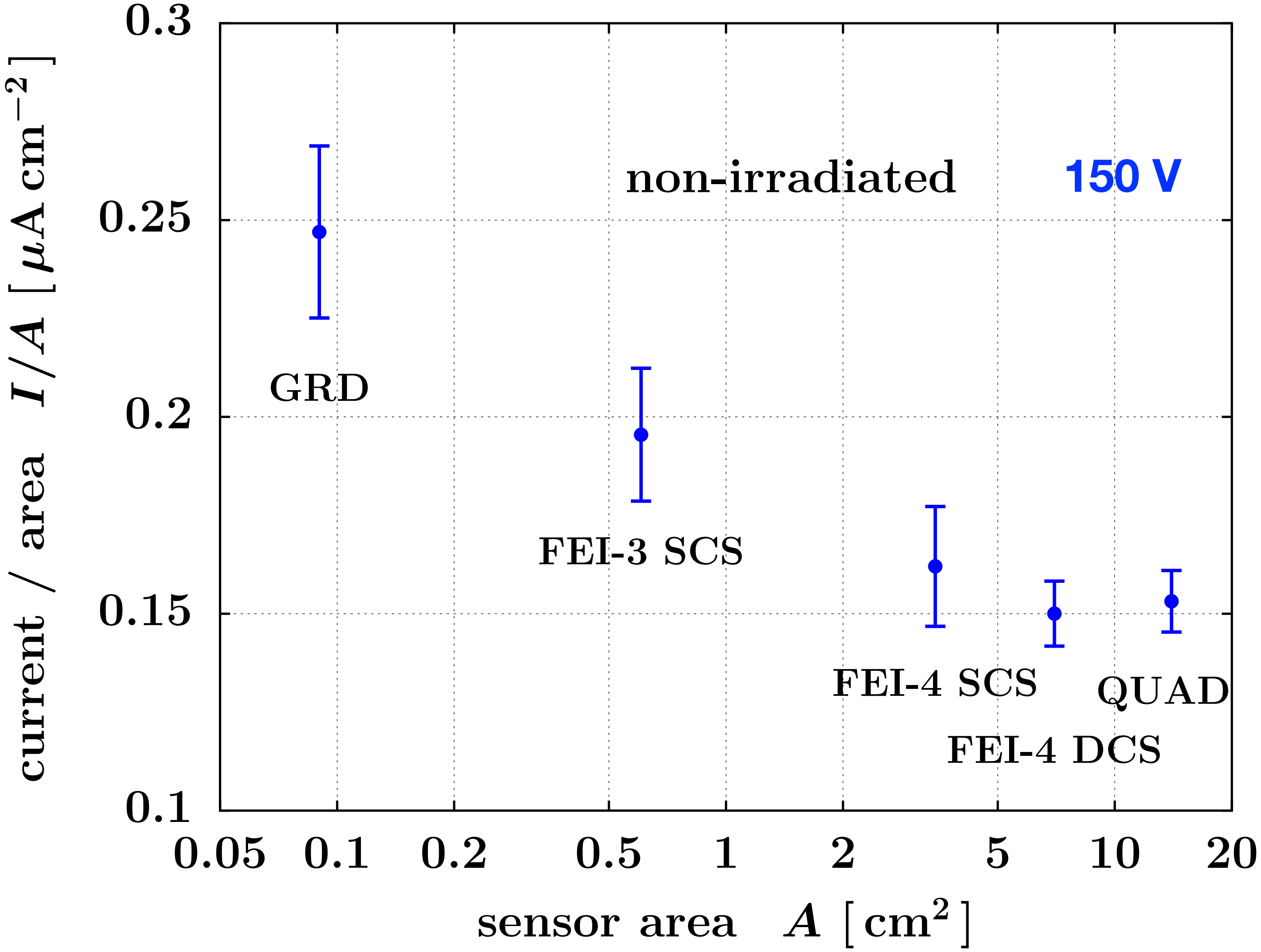
250 µm

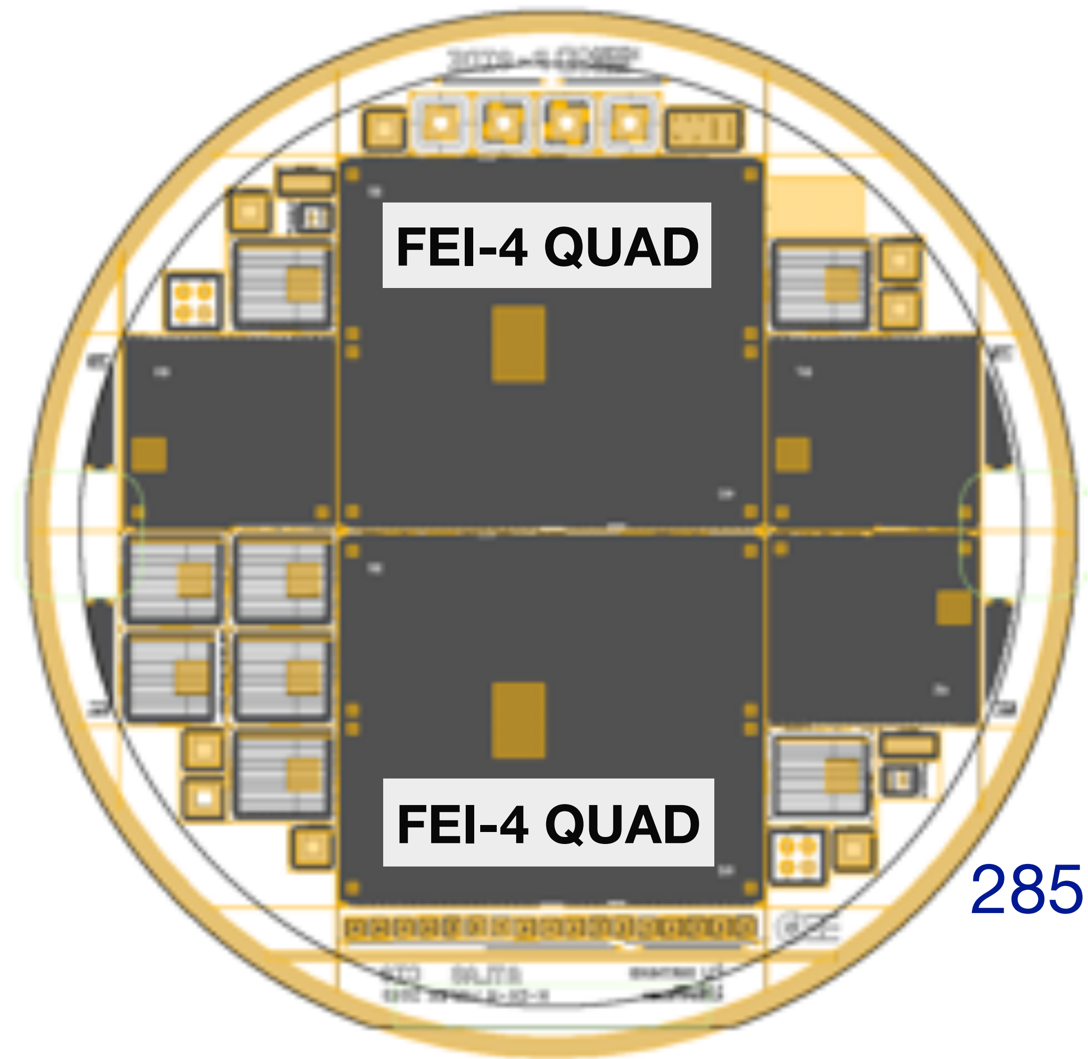
- leakage current per sensor area decreases with increasing sensor area
- measurements were carried out on a non-diced, non-irradiated wafer

study by
Andreas Gisen

Leakage Current Area Densities *vs*. Sensor Area, non-irradiated

HL-LHC upgrade
prototype wafer 2014





design by Tobias Wittig

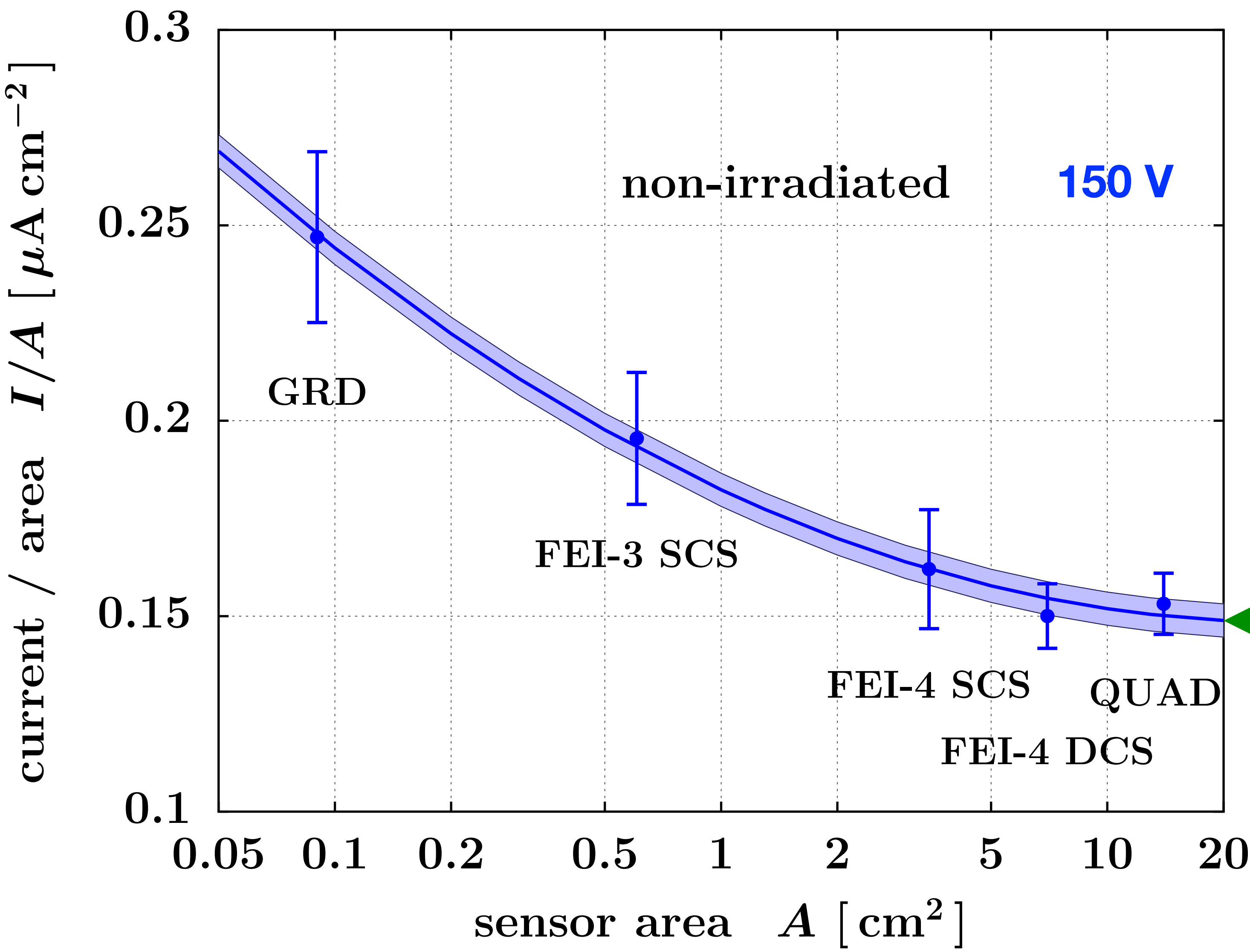
285 µm

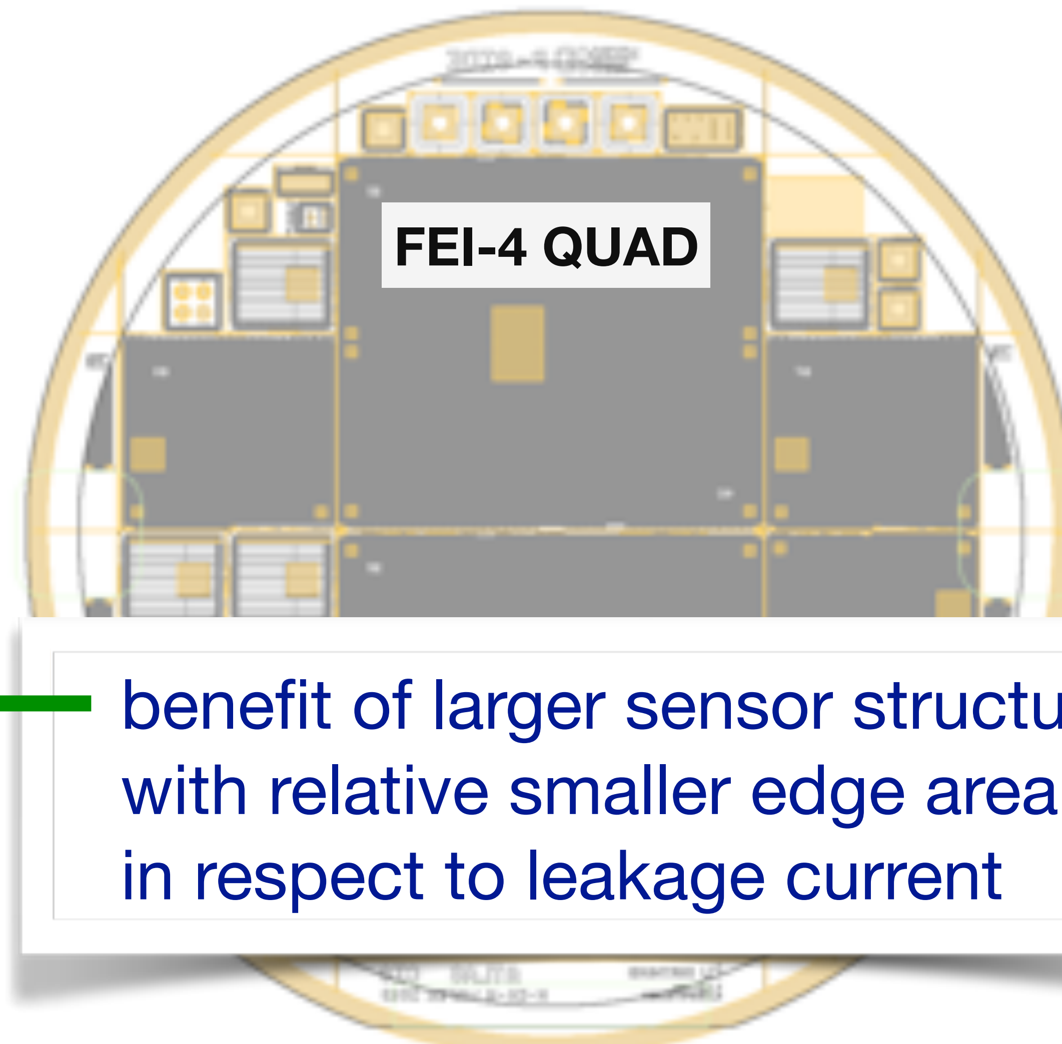
- leakage current per sensor area decreases with increasing sensor area
- measurements were carried out on a non-diced, non-irradiated wafer
- comparison includes prototype wafers with FEI-4 QUAD sensors

study by
Andreas Gisen

Leakage Current Area Densities *vs*. Sensor Area, non-irradiated

HL-LHC upgrade
prototype wafer 2014





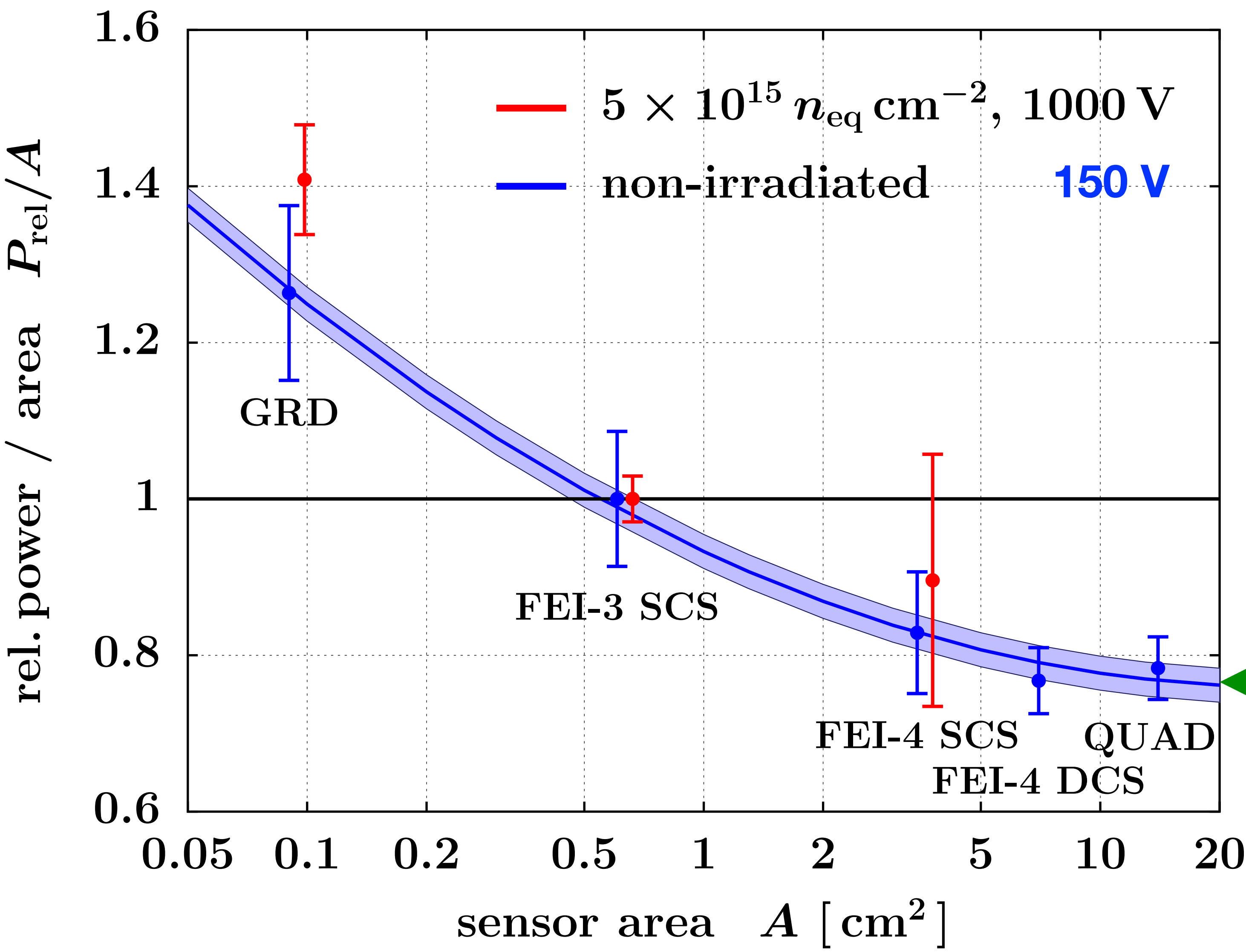
design by Tobias Wittig

benefit of larger sensor structures
with relative smaller edge area
in respect to leakage current

- leakage current per sensor area decreases with increasing sensor area
- measurements were carried out on a non-diced, non-irradiated wafer
- comparison includes prototype wafers with FEI-4 QUAD sensors

Relative Power Dissipation Area Densities *vs*. Sensor Area, irradiated *vs*. non-irradiated

measurements by Sascha Dungs Carolin Ratering Silke Altenheiner



comparison to data of diced & irradiated sensor structures

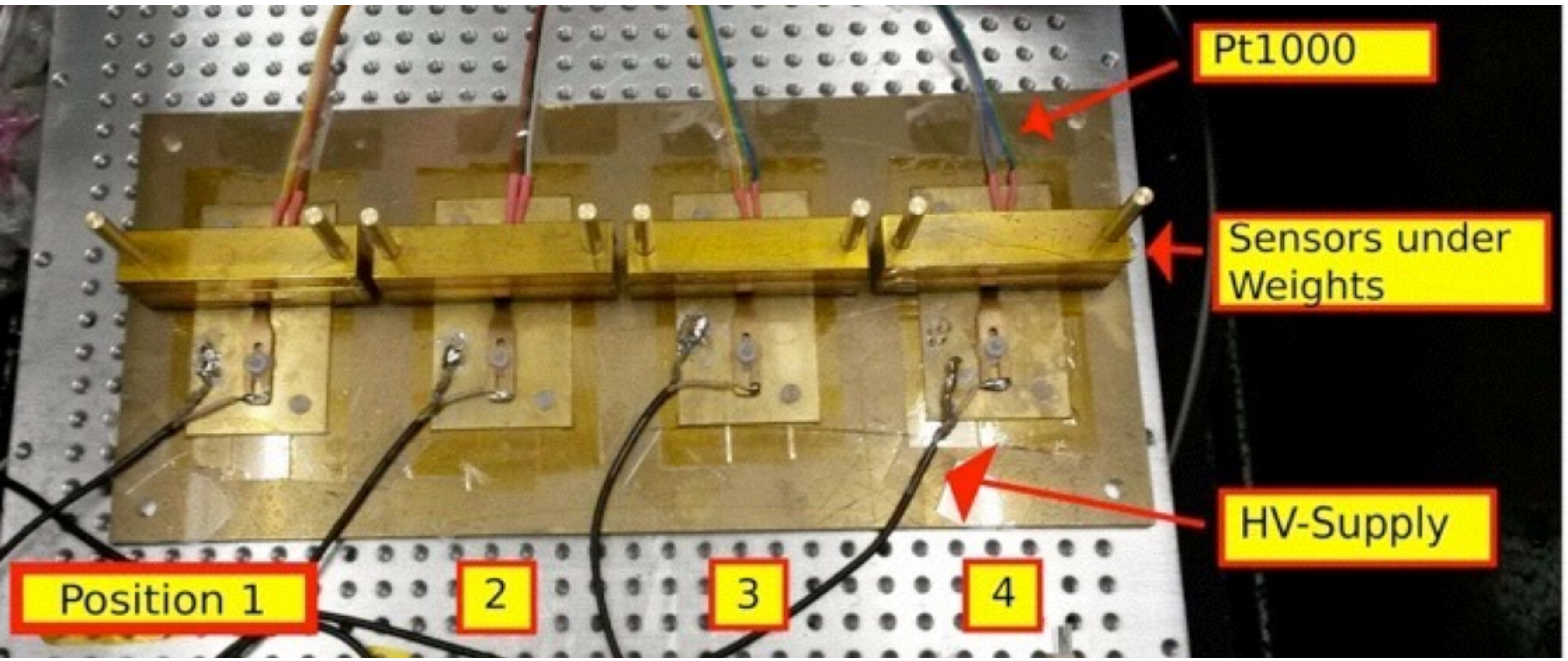
FEI-4 single chip sensors include samples w/ neutron or proton irradiations @ $5{\times}10^{15}\ n_{eq}\ cm^{-2}$

benefit of larger sensor structures with relative smaller edge area in respect to power dissipation

- relative power dissipation per sensor area decreases with increasing sensor area
- agreement of data between irradiated & non-irradiated structures

Leakage Current
vs. Irradiation Fluence — up to HL-LHC Fluences

set-up by
Bettina Hillringhaus



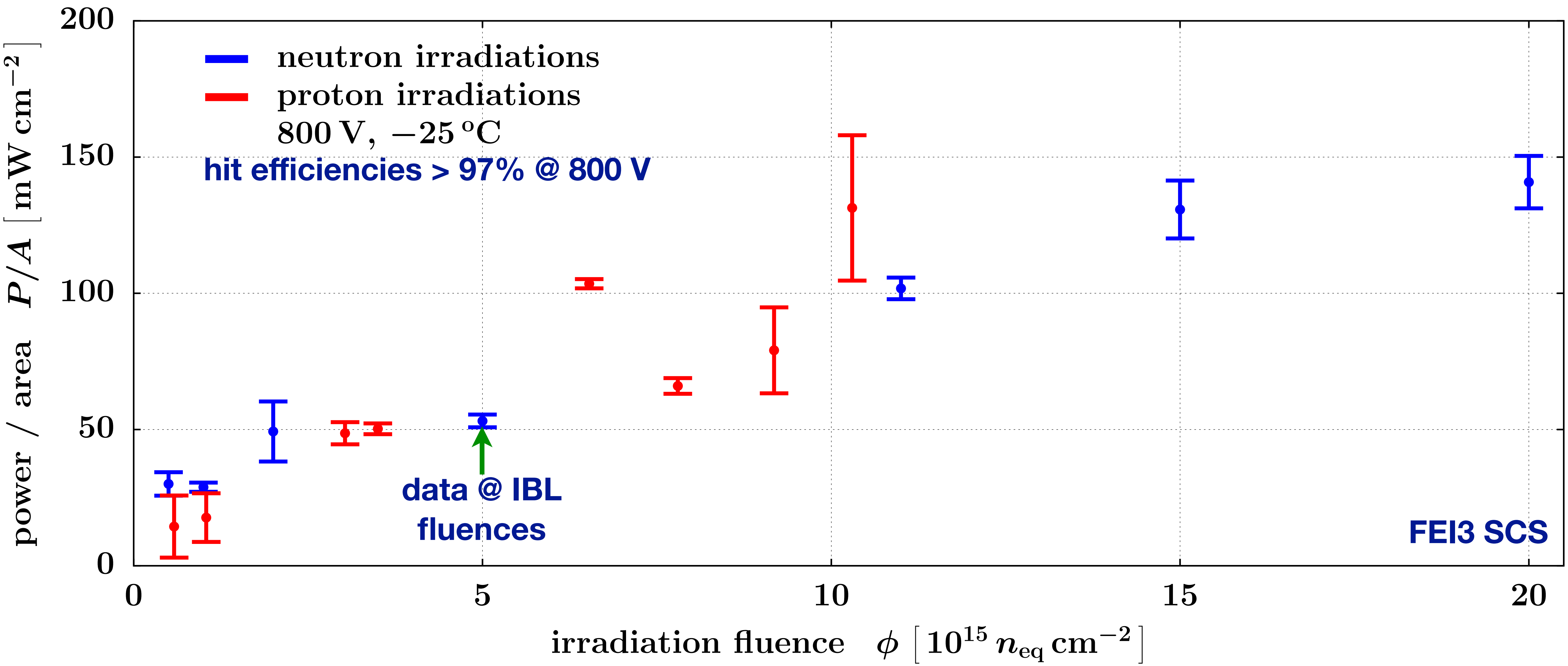
- bare sensors w/o any front-end are connected to a cooling plate
- optimized for best cooling contact
- measure 4 sensors simultanously to reduce systematics

irradiated FEI-3-sized single chip sensors are investigated

- reactor neutrons @ Ljubljana up to $20\times10^{15}\ n_{eq}\ \mathrm{cm}^{-2}$
- protons @ CERN & Karlsruhe up to $10\times10^{15}\ n_{eq}\ \mathrm{cm}^{-2}$

measurements by
Bettina Hillringhaus

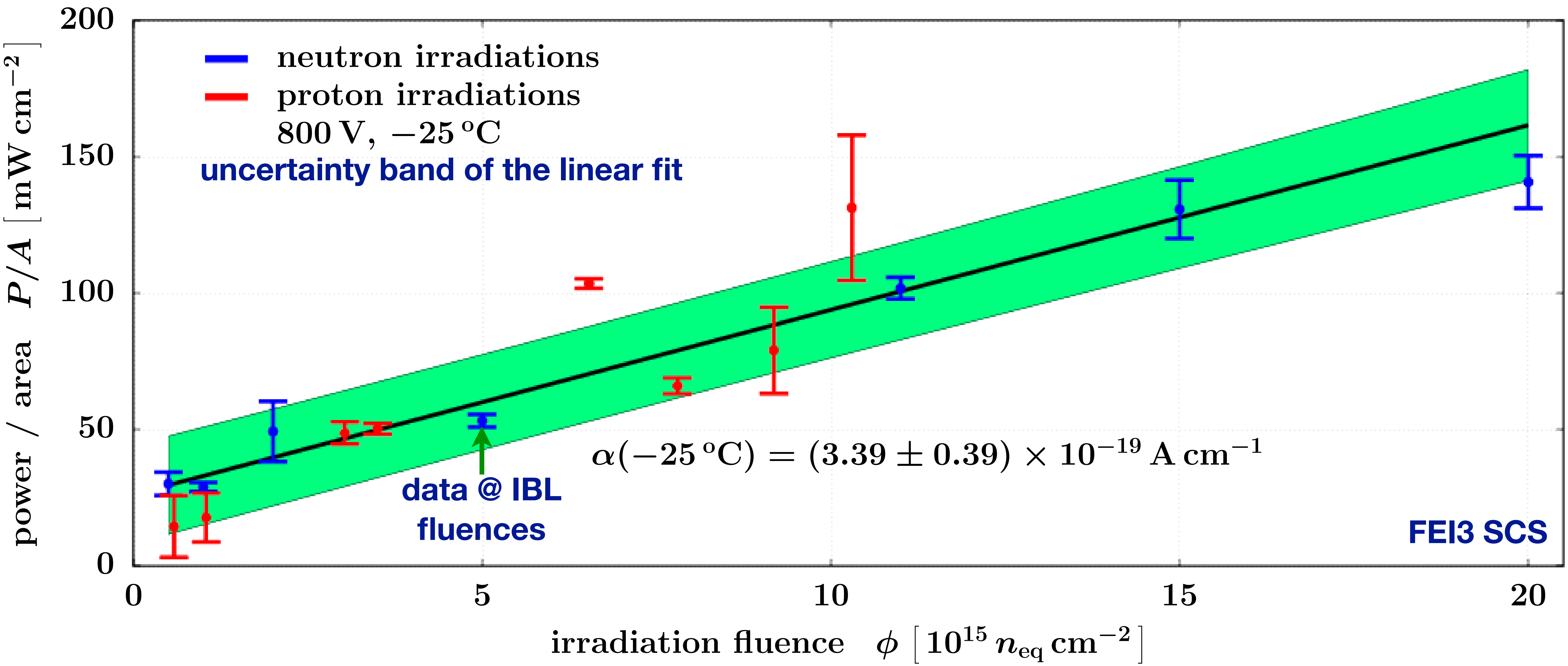
Power Dissipation Area Density *vs*. Irradiation Fluence — up to HL-LHC Fluences



- measured power dissipations are below 150 mW cm^{-2}

measurements by
Bettina Hillringhaus

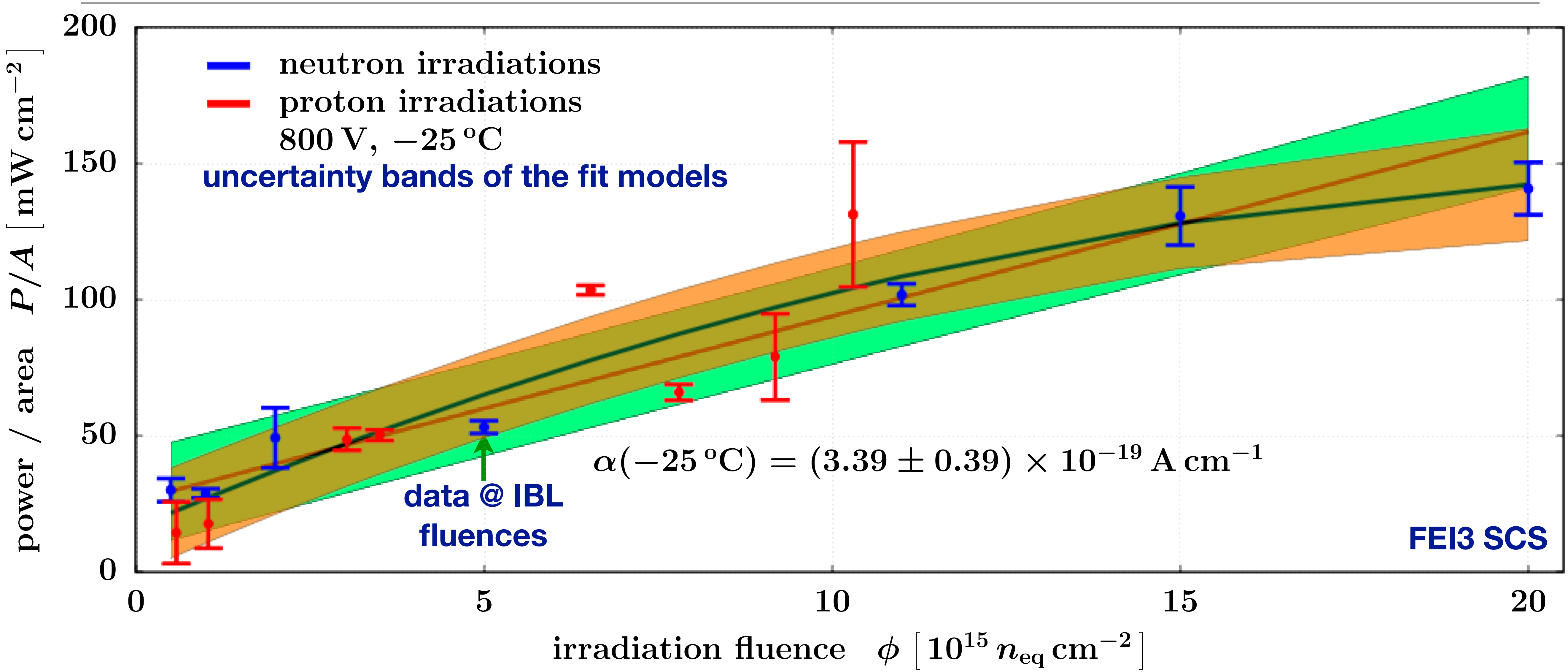
Power Dissipation Area Density *vs*. Irradiation Fluence — up to HL-LHC Fluences



- consistent leakage current increase with fluence, $\alpha=\Delta I/(V\phi)$

measurements by
Bettina Hillringhaus

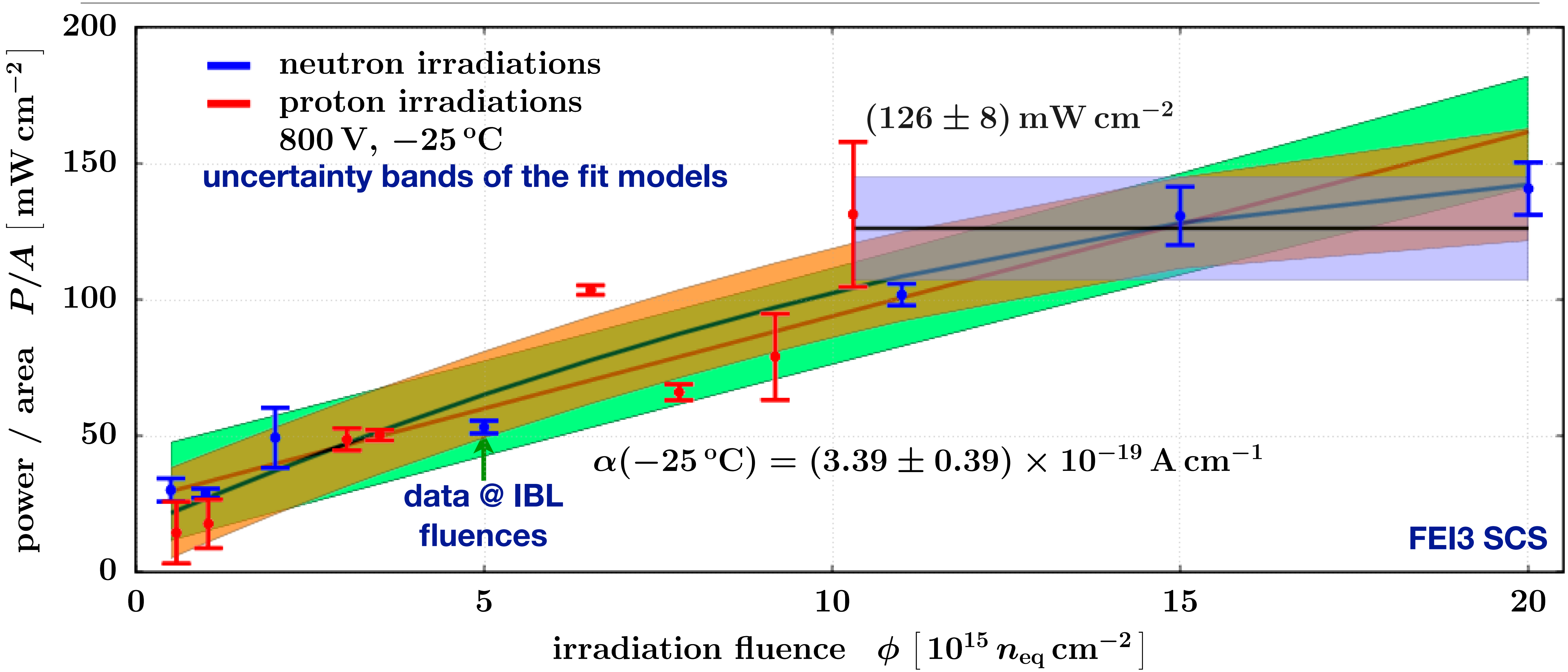
Power Dissipation Area Density *vs*. Irradiation Fluence — up to HL-LHC Fluences



- consistent leakage current increase with fluence, α=ΔI/(Vϕ)
- is already some saturation visible at high fluences?

cf. Kramberger et al., JINST ***8*** *(2013) P08004*

Power Dissipation Area Density *vs*. Irradiation Fluence — up to HL-LHC Fluences



- consistent leakage current increase with fluence, α=ΔI/(Vϕ)
- is already some saturation visible at high fluences?
- HL-LHC: (126±8) mW cm^{-2} → ~100 mW cm^{-2} on large sensors

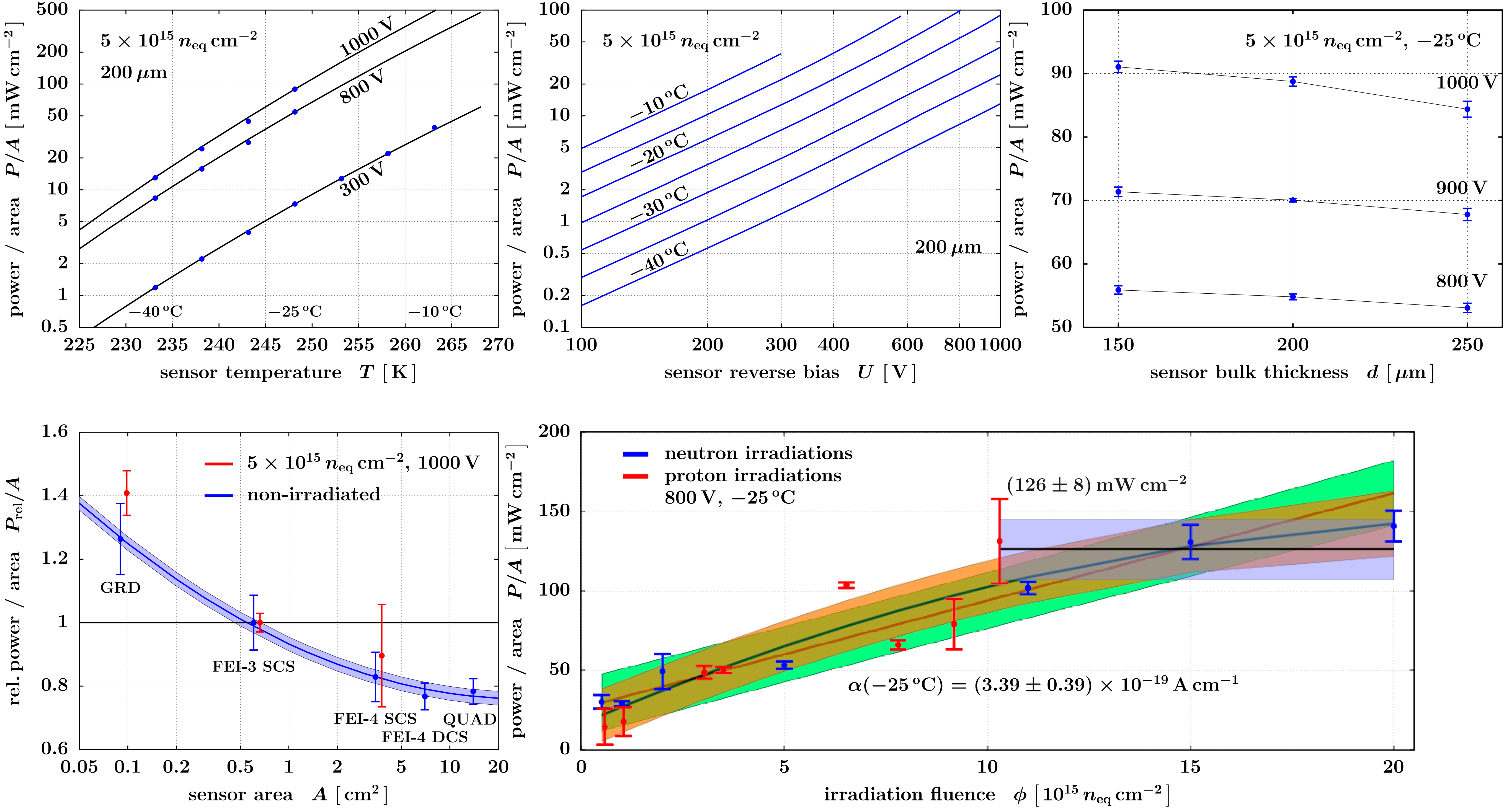
cf. G. Kramberger et al., JINST ***8*** *(2013) P08004*

FEI3 SCS **FEI4 DCS + QUAD**

Summary

technische universität
dortmund

Power Dissipation Studies on n⁺-in-n Pixel Sensors

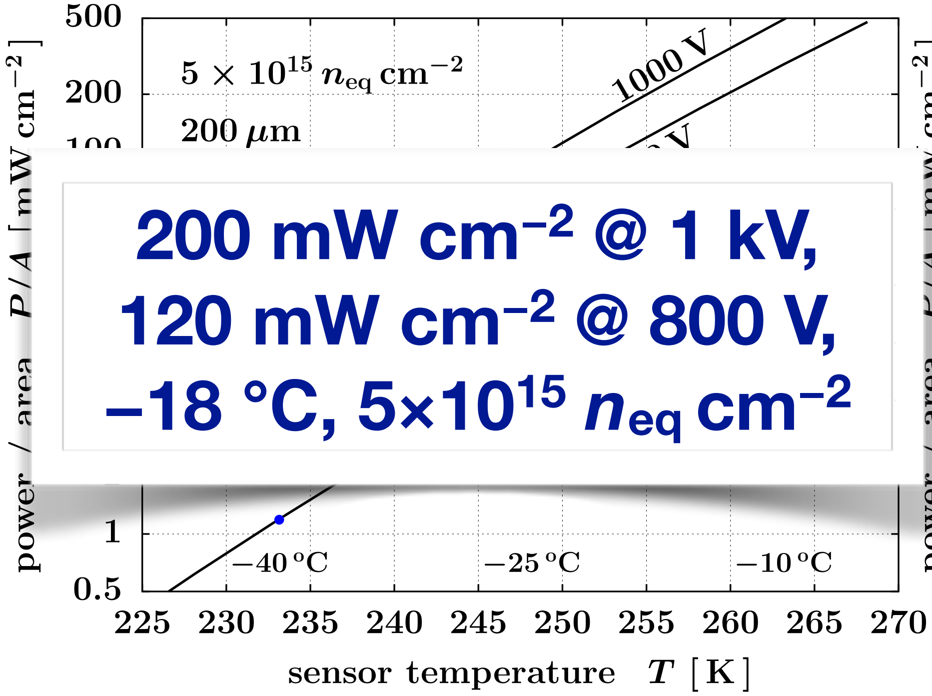


Reiner Klingenberg, TU Dortmund University

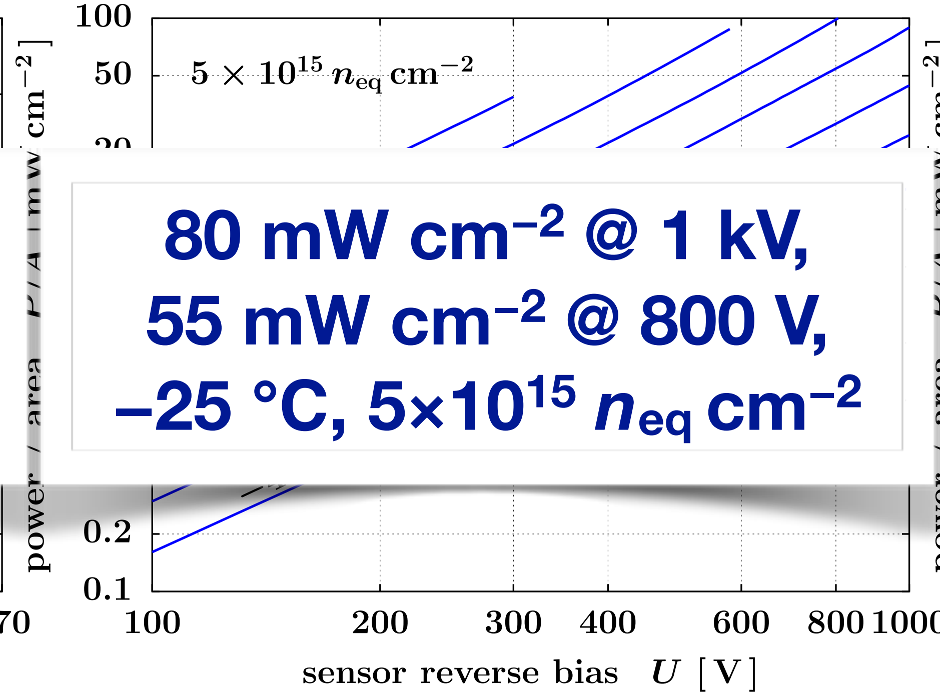
Summary

technische universität dortmund

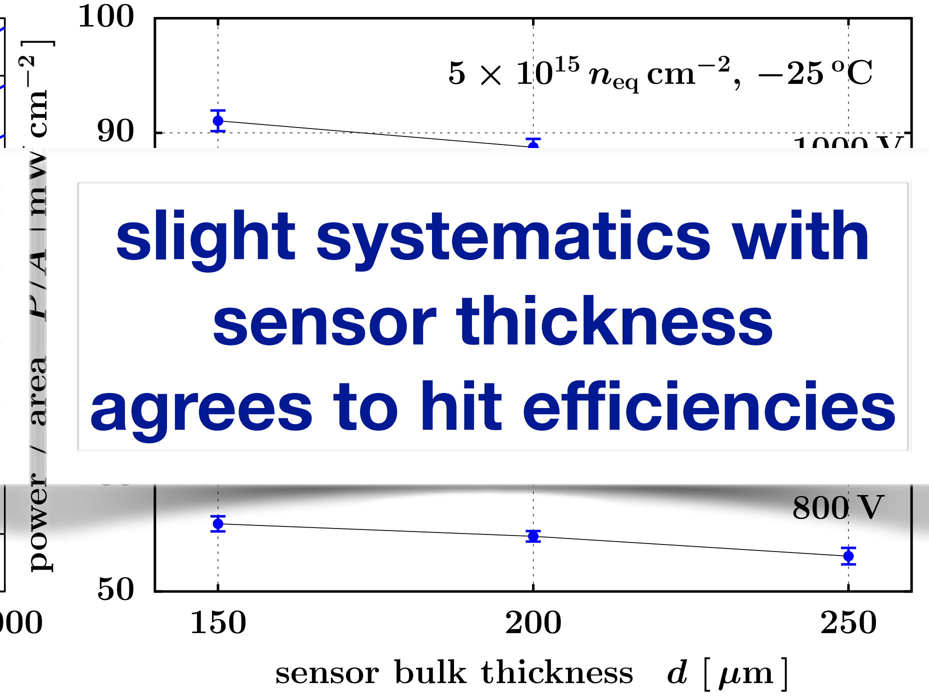
Power Dissipation Studies on n⁺-in-n Pixel Sensors



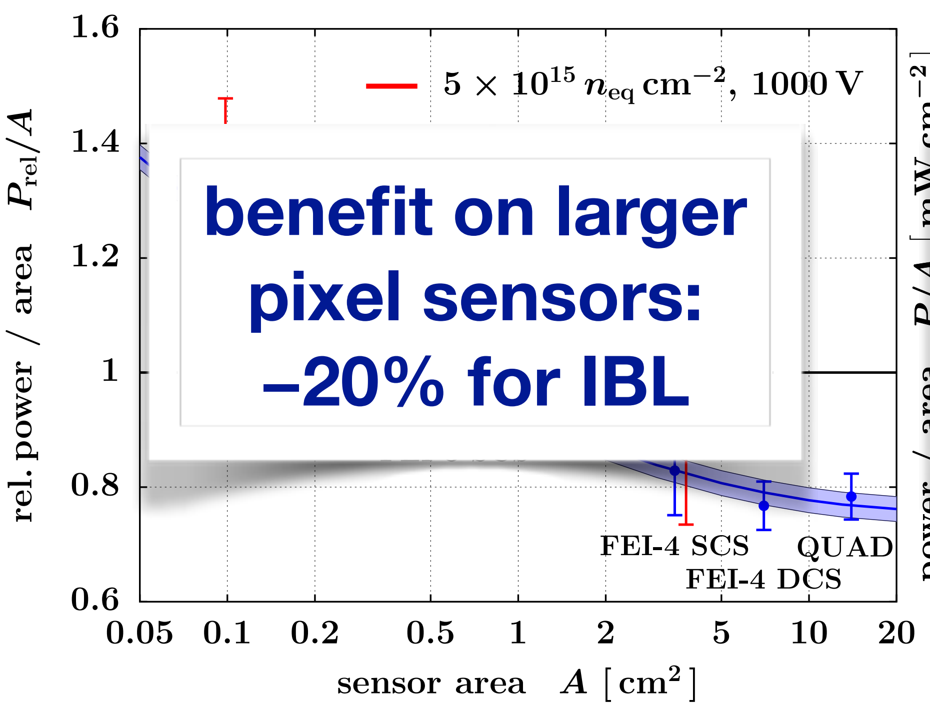
200 mW cm⁻² @ 1 kV, 120 mW cm⁻² @ 800 V, –18 °C, 5×10¹⁵ n_{eq} cm⁻²



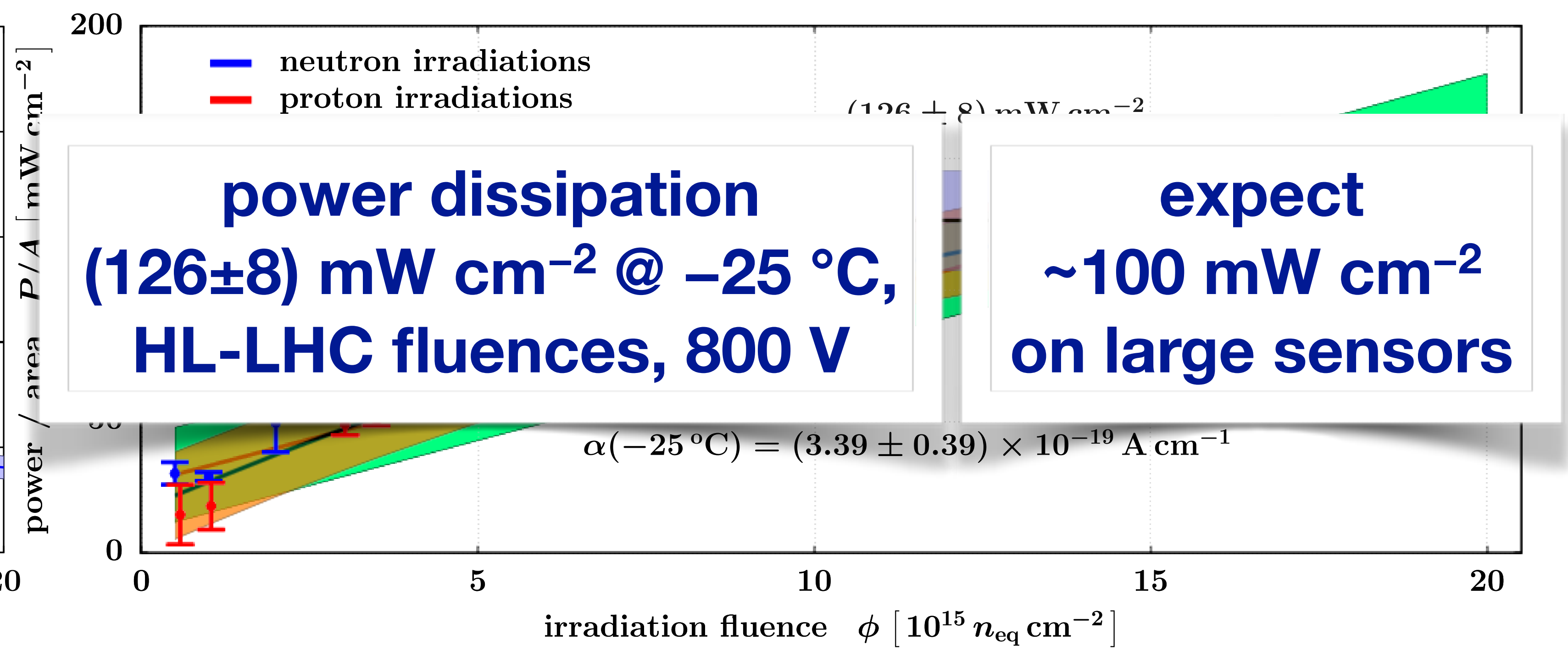
80 mW cm⁻² @ 1 kV, 55 mW cm⁻² @ 800 V, –25 °C, 5×10¹⁵ n_{eq} cm⁻²



slight systematics with sensor thickness agrees to hit efficiencies



benefit on larger pixel sensors: –20% for IBL



power dissipation (126±8) mW cm⁻² @ –25 °C, HL-LHC fluences, 800 V

expect ~100 mW cm⁻² on large sensors

Reiner Klingenberg, TU Dortmund University