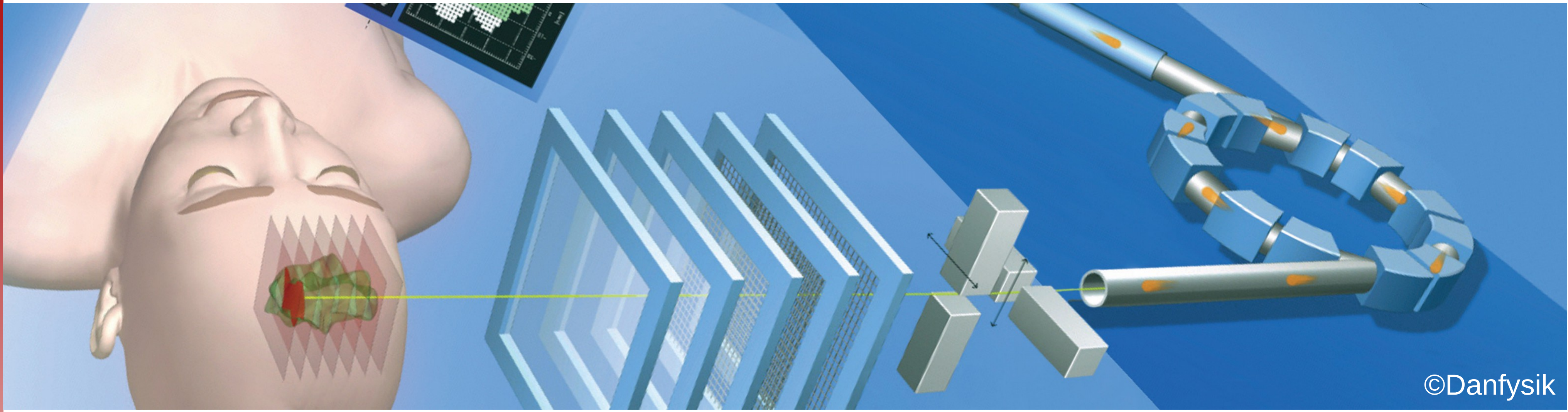
CMOS applications for charged particle detection (nuclear/mass spectroscopy/medical)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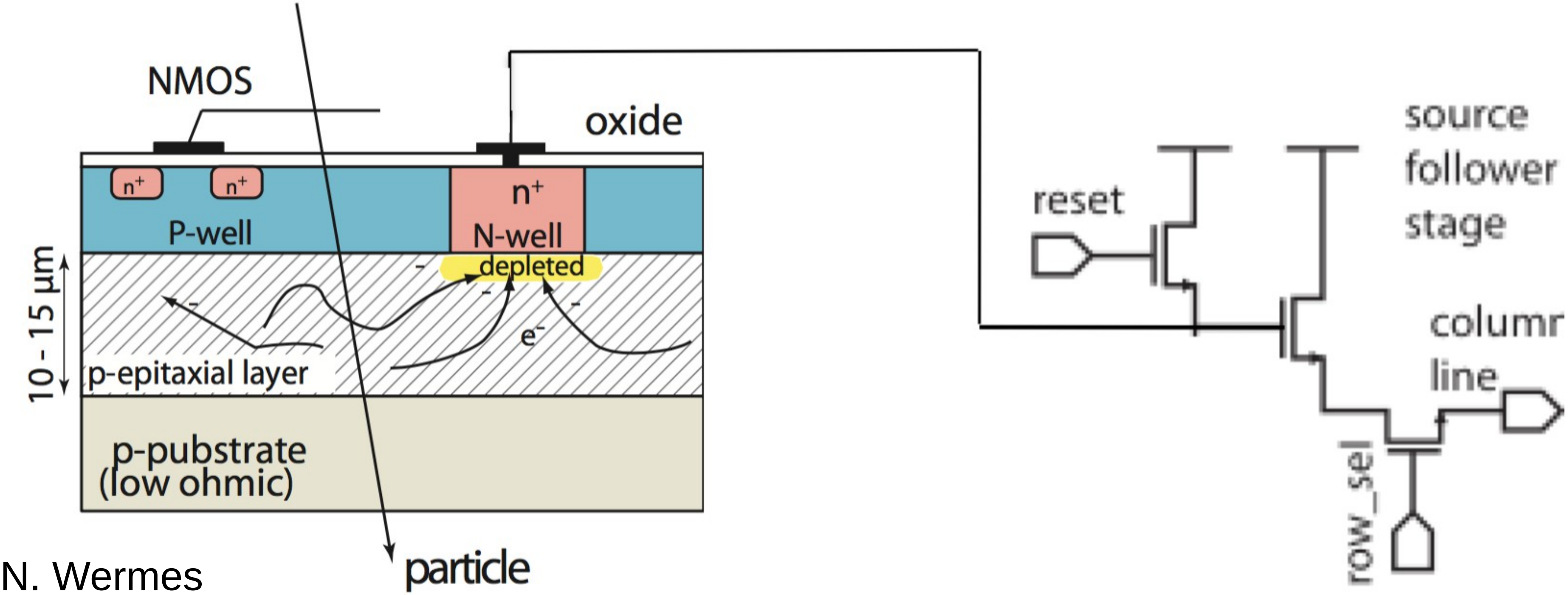
Scope of this talk

- I was asked to give an overview/a sample of potential applications for CMOS sensors beyond particle physics focussing on detection of charged particles
- Disclaimer: I am not an expert for most of the applications discussed
  - take my slides with a grain of salt
  - let me know if you spot any obvious mistakes

- There have already been dedicated particle sensors (often designated as monolithic active pixel sensors or “MAPS”) for a rather long time, but
  - these were usually relying on diffusion as means of charge collection
    - slow
    - fails already for comparatively low amounts of trapping from (bulk) radiation damage
- The same is (mostly) true for classical CMOS imaging sensors which enabled to have cameras in virtually all everyday gadgets like mobile phones
- I will try to point out potential applications of drift-based CMOS sensors

Charged particle detection in CMOS

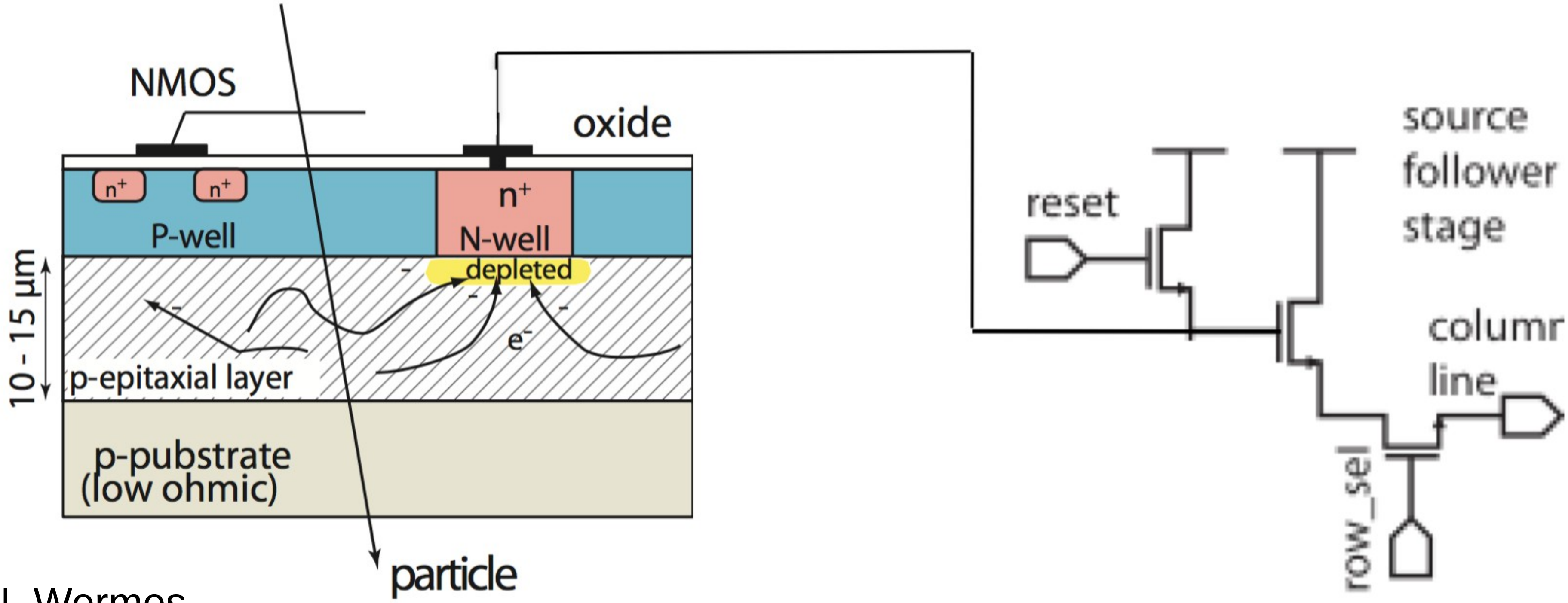
- Main idea: electrons (or holes) survive long enough to reach collection electrodes
  - use high-grade silicon layer to accomplish → epi
  - rely on diffusion → slow, not rad-hard
- use built-in voltage at pn-junction to collect charge, use small capacitance of electrode to reach sufficient voltage levels
- classical readout scheme: 3/4/5 transistor, requires reset, does usually not account for leakage current, rolling shutter/sequential readout (slow)



N. Wermes

Charged particle detection in CMOS

- Advantages of MAPS sensors
  - small pixel sizes possible
  - readout electronics mostly integrated in sensor
  - cost-efficient production
- Disadvantages of MAPS sensors
  - not radiation-tolerant
  - comparatively bad timing
  - depending on readout scheme: slow, inevitable dead-time, no self-trigger

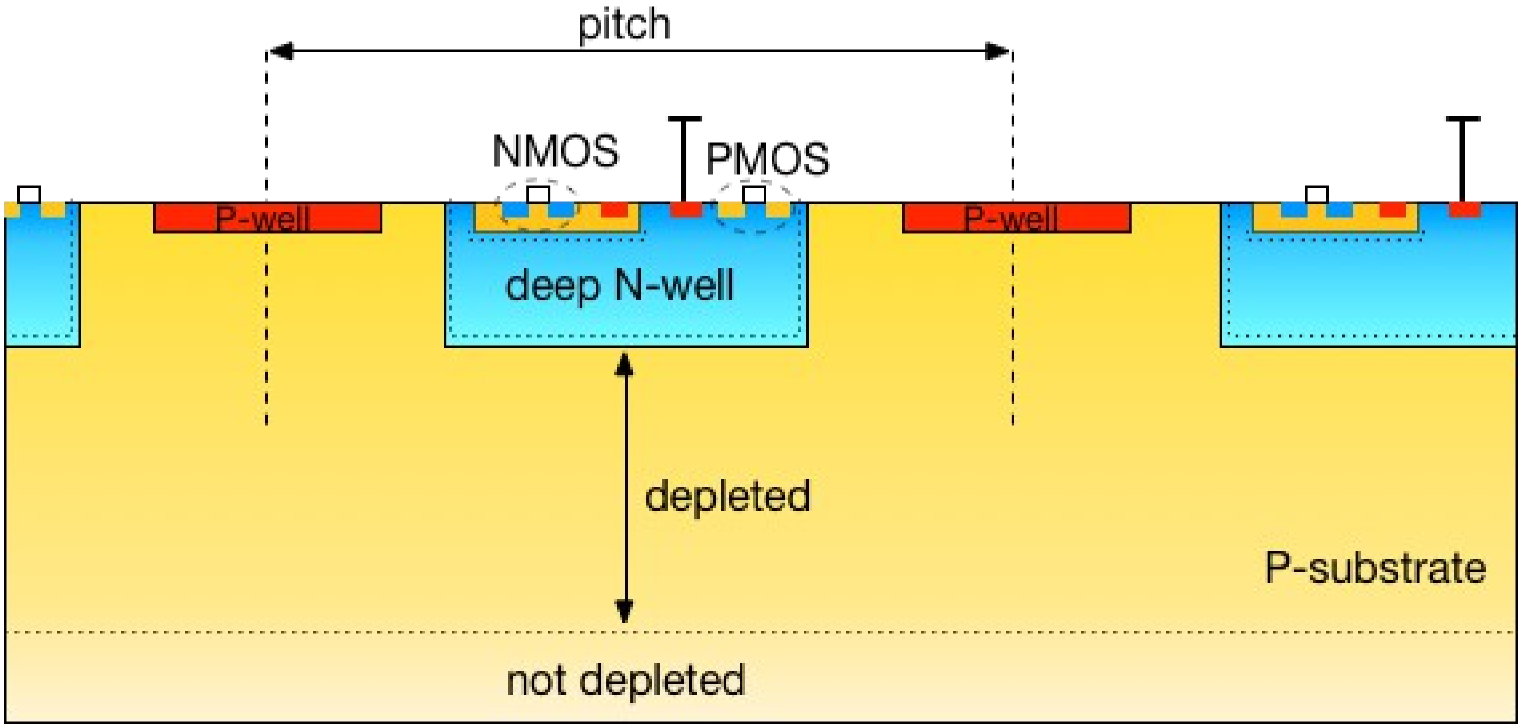


N. Wermes

“Classical MAPS” → HV/HR-CMOS

- Apply bias voltage to bulk → rely on drift instead of diffusion
- Avoid charge collection on parasitic wells by shielding them inside a deep n-well
- Take care of inter-pixel isolation after irradiation by suitable techniques
- Often a rather classical charge-sensitive amplifier with leakage current compensation is used at the expense of larger pixels

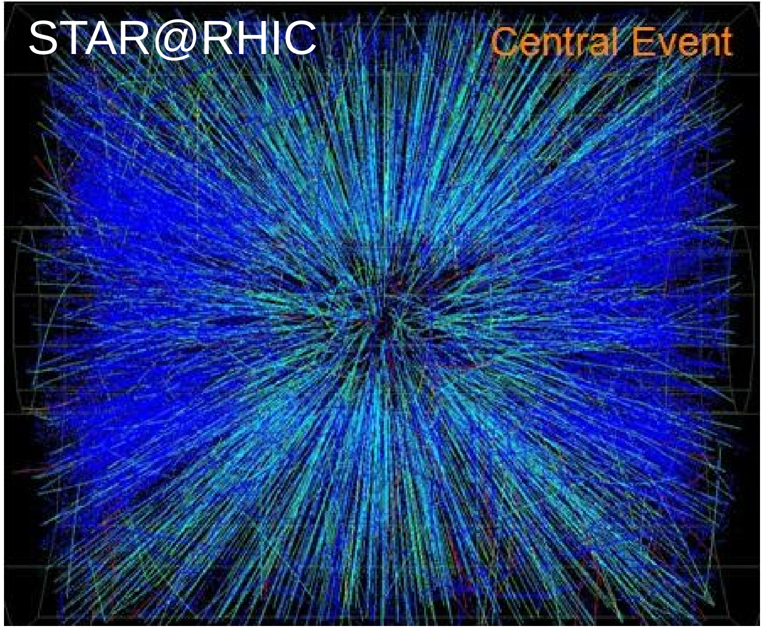
- New applications opening up?

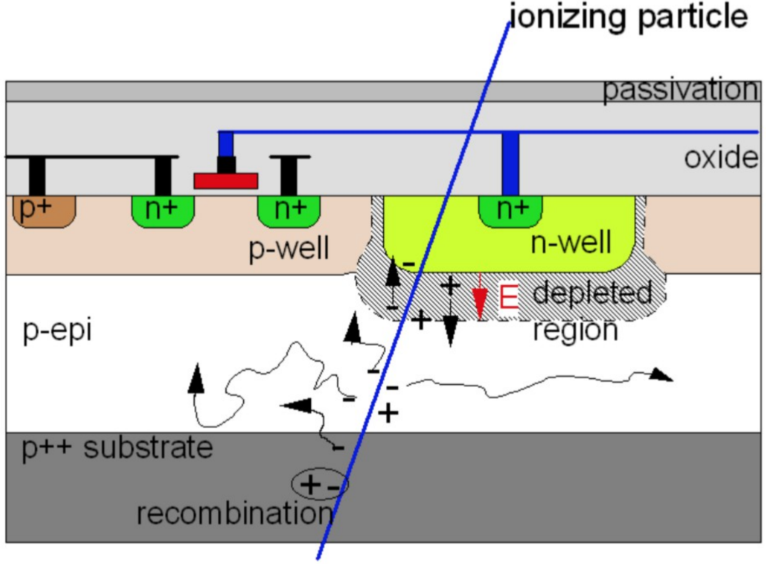


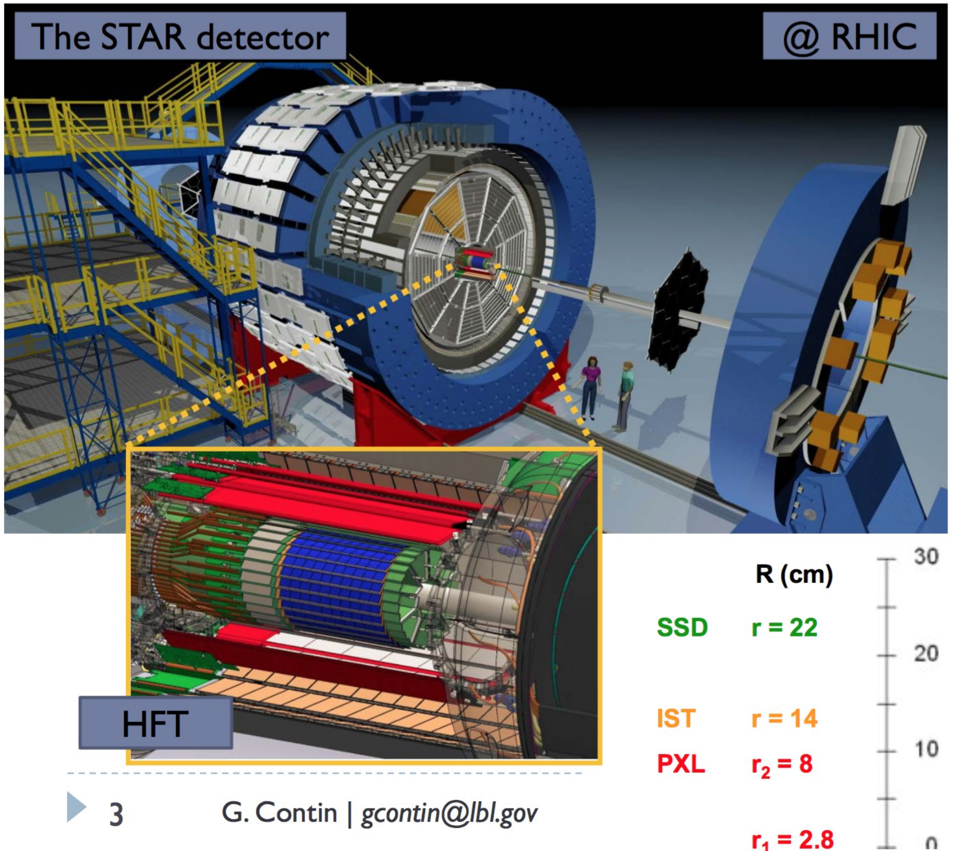
Nuclear Physics Applications

- Classical application: Particle tracking
  - not particle physics? → Similar, but still different
    - often large multiplicities
    - particle energies
  - Particle/Hadron/Nuclear physics?
- Examples:
  - STAR
  - Panda Luminosity Monitor

- STAR (→ Petra Riedler's talk)
  - AMS 350nm opto process (C35O)

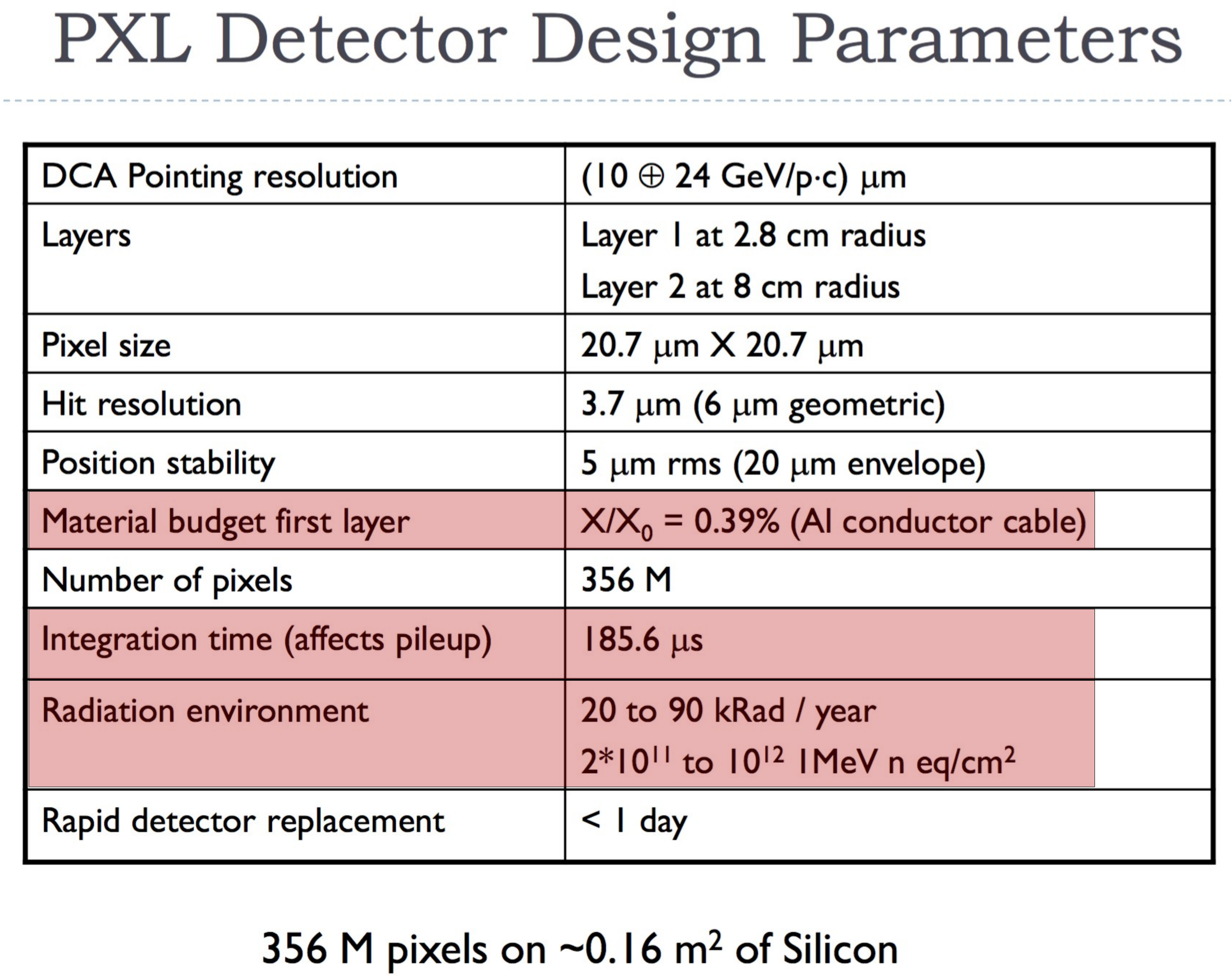






Nuclear Physics Applications

- STAR
  - rather moderate radiation environment
  - material budget rather low
  - timing generous



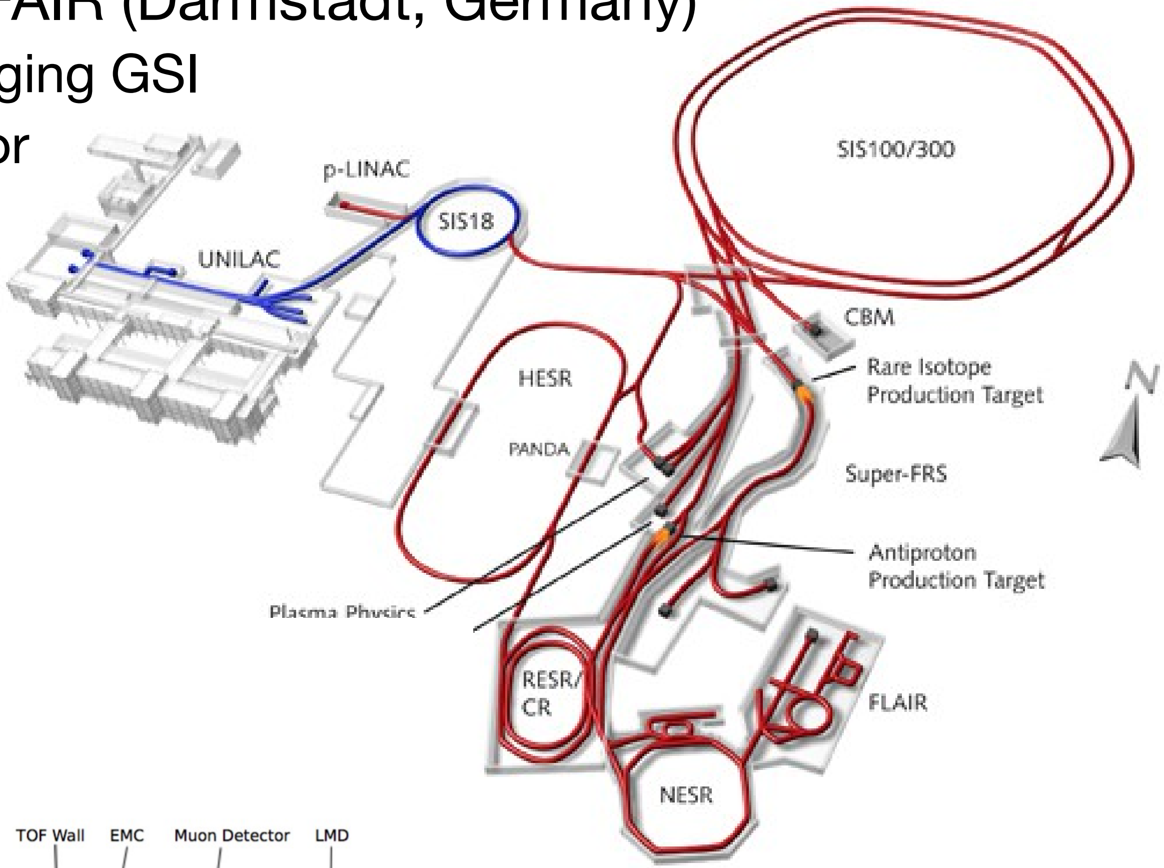
PXL Detector Design Parameters

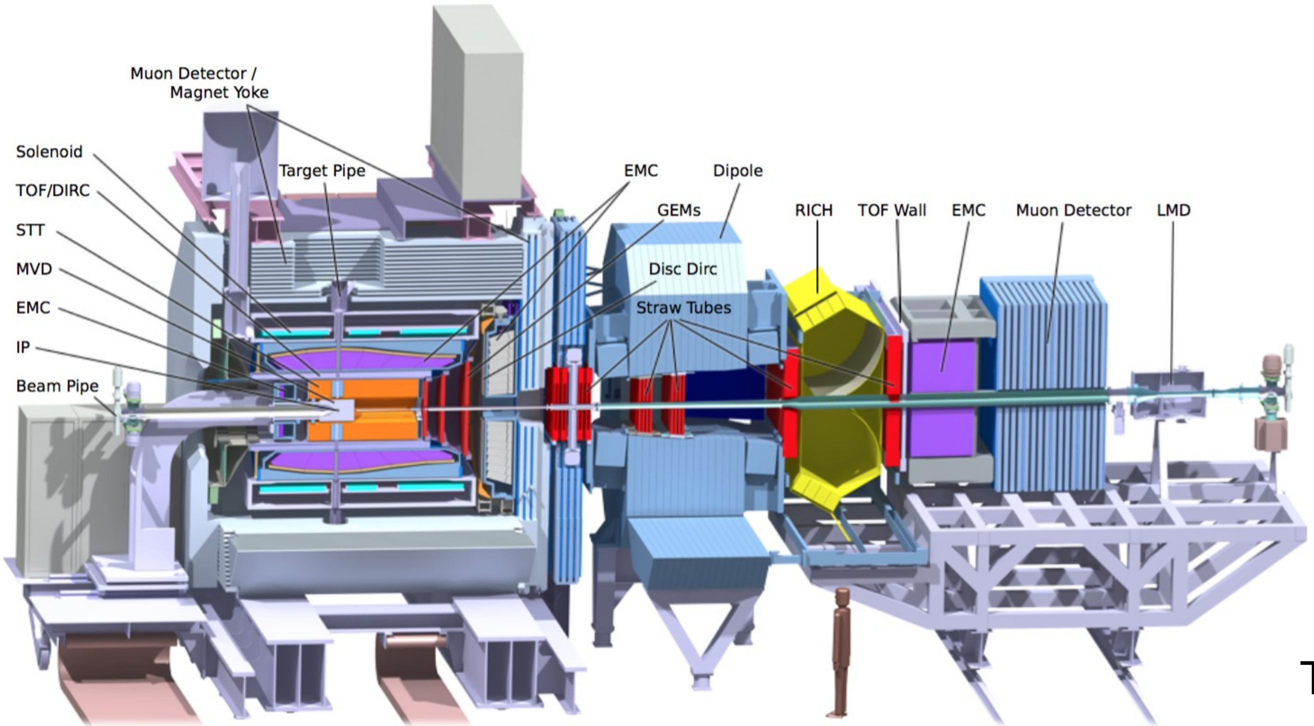
DCA Pointing resolution	(10 ⊕ 24 GeV/p·c) μm
Layers	Layer 1 at 2.8 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 μm X 20.7 μm
Hit resolution	3.7 μm (6 μm geometric)
Position stability	5 μm rms (20 μm envelope)
Material budget first layer	X/X_0 = 0.39% (Al conductor cable)
Number of pixels	356 M
Integration time (affects pileup)	185.6 μs
Radiation environment	20 to 90 kRad / year $2*10^{11}$ to 10^{12} 1MeV n eq/cm^2
Rapid detector replacement	< 1 day

356 M pixels on ~0.16 m^2 of Silicon

Nuclear Physics Applications

- Panda Luminosity Monitor @ FAIR (Darmstadt, Germany)
  - ongoing site construction enlarging GSI
  - Panda being a versatile detector for proton-antiproton collisions
    - hadron spectroscopy
    - nucleon structure
    - hadrons in matter
    - hypernuclei

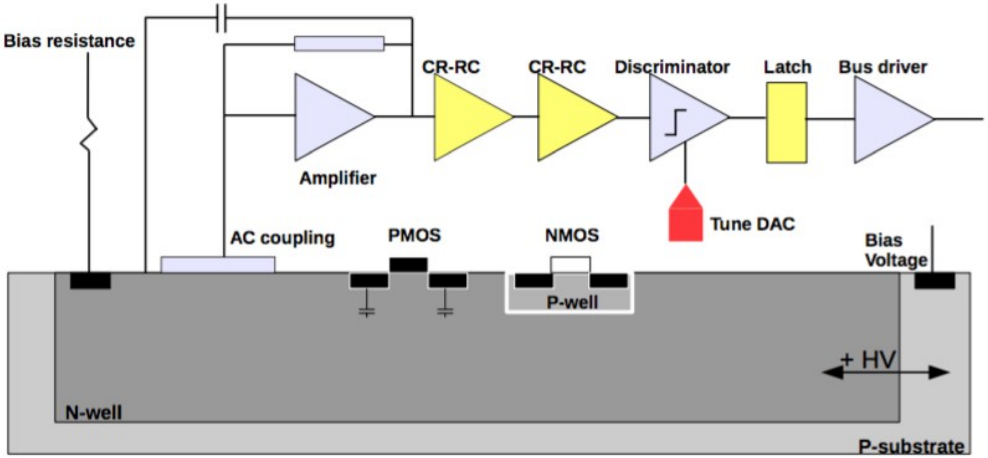


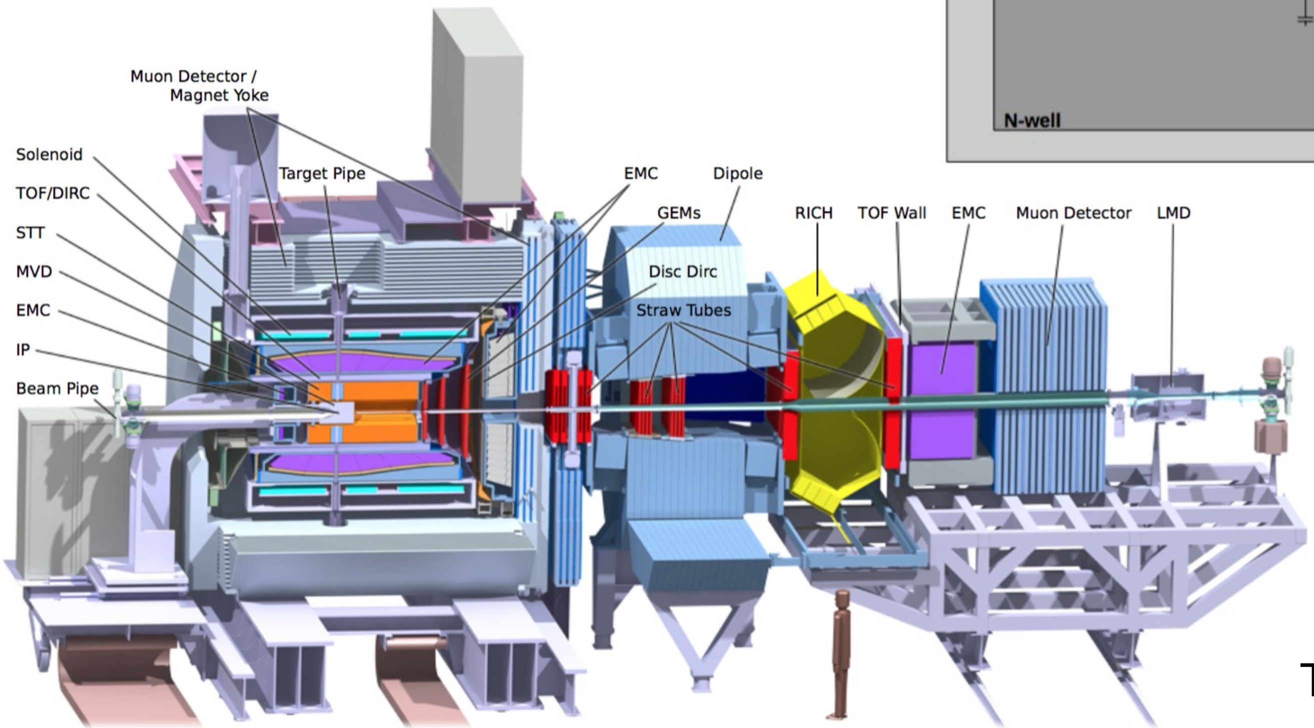


Tobias Weber

Nuclear Physics Applications

- Panda Tracking system
  - Several gas-based detectors
  - Double-sided silicon strips for the Micro-Vertex-Detector
    - radiation hardness for hole collection already marginal (CMOS too late)?
  - Luminosity Monitor expected to use HV-MAPS
    - MuPix type, identical to μ3e chip
      - → see Heiko Augustin's talk





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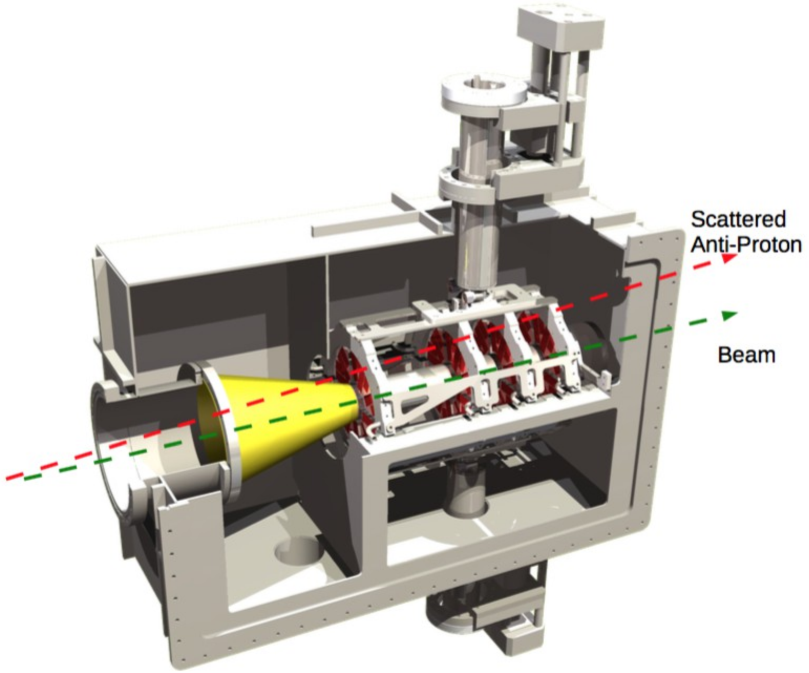
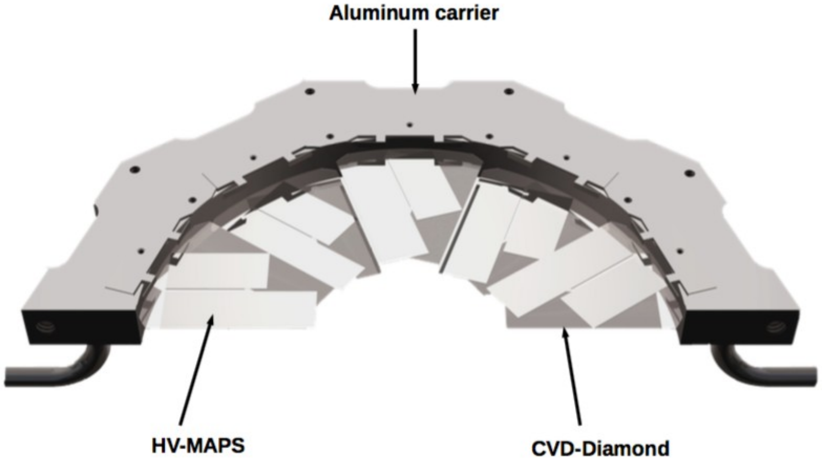
Nuclear Physics Applications

- Panda Tracking system
  - basic idea: mount HV-MAPS chips to CVD diamond substrate to provide cooling
    - very thin/low X0 configuration possible
    - HV-CMOS sensors tolerate running at rather high temperatures and with significant Delta-T across the sensor





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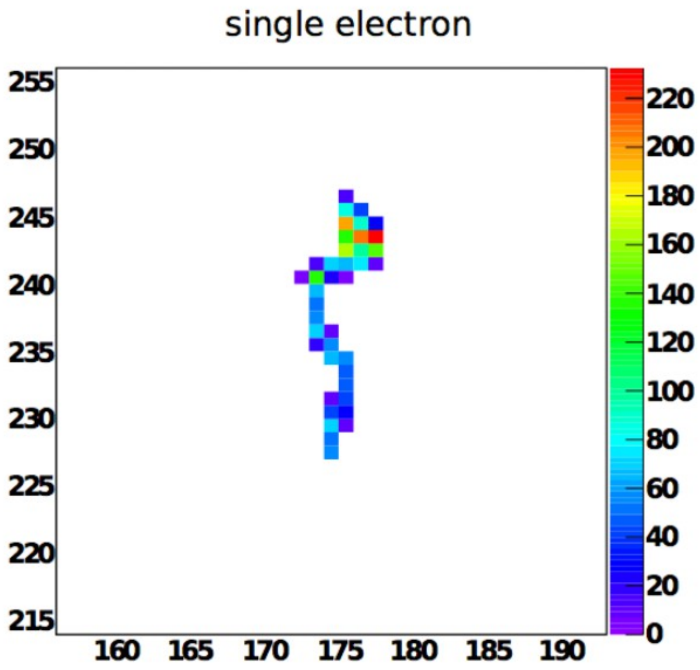
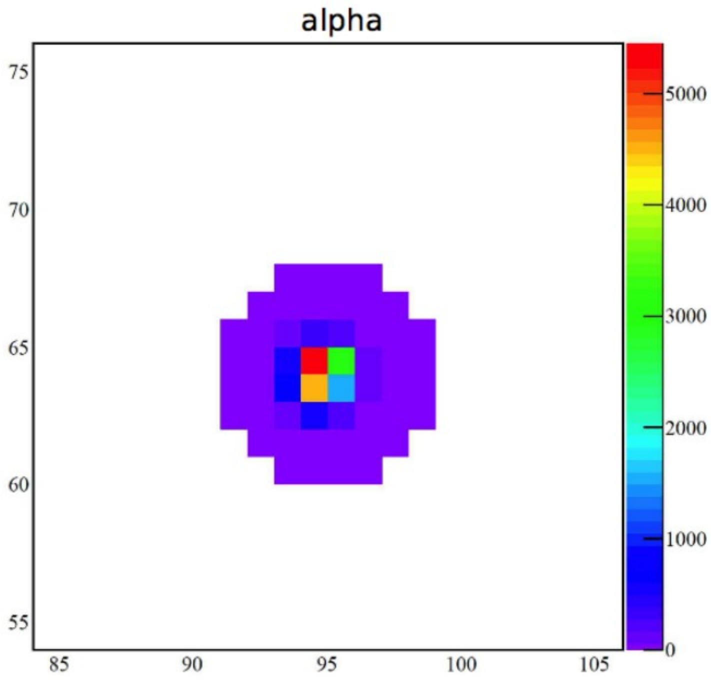
Further “Nuclear” Applications

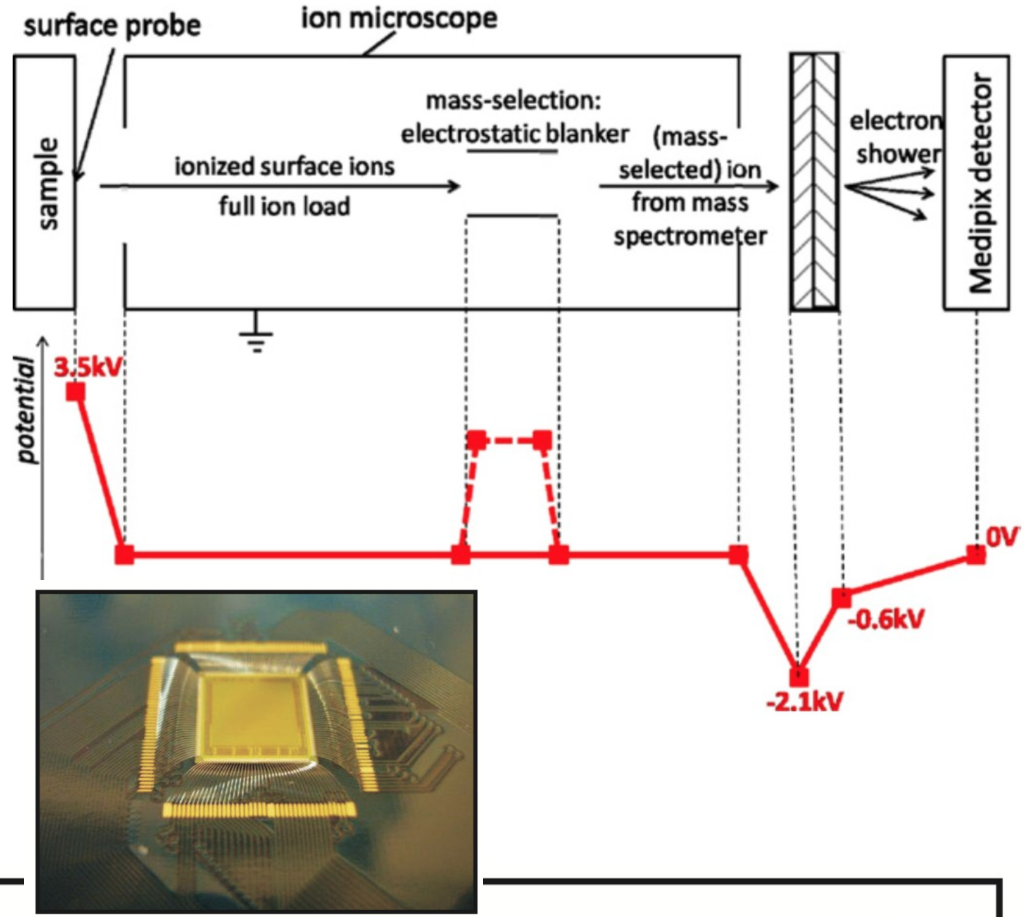
- Most nuclear physics applications are based on detection/spectroscopy of gamma rays
  - not ideal
- But Particle ID is possible
- Potential instrumentation for “nuclear” things:
  - contamination monitors: large areas, currently ionisation chambers or scintillators for beta (and alpha) detection
  - tritium detection: low-energy beta (14 keV), short range

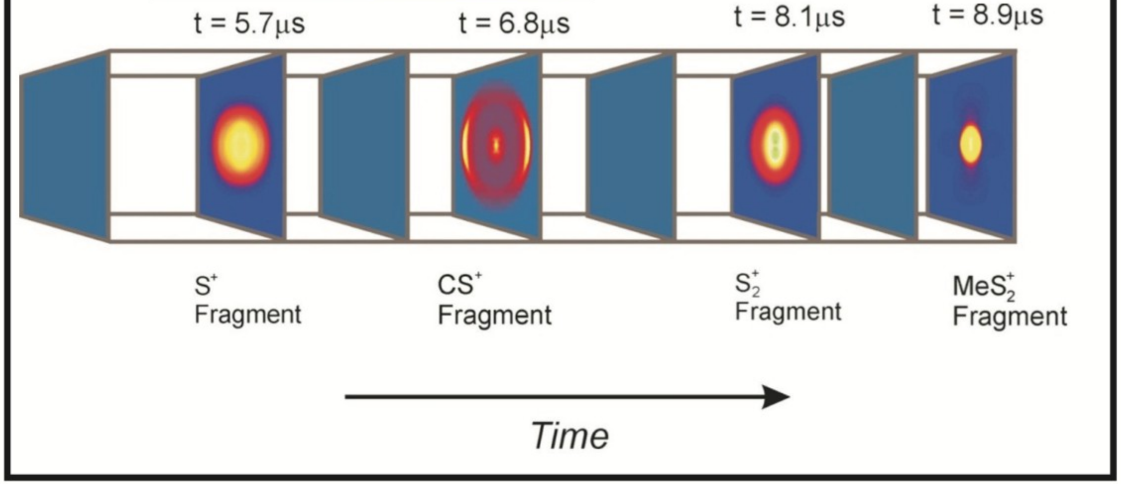




Mass spectroscopy

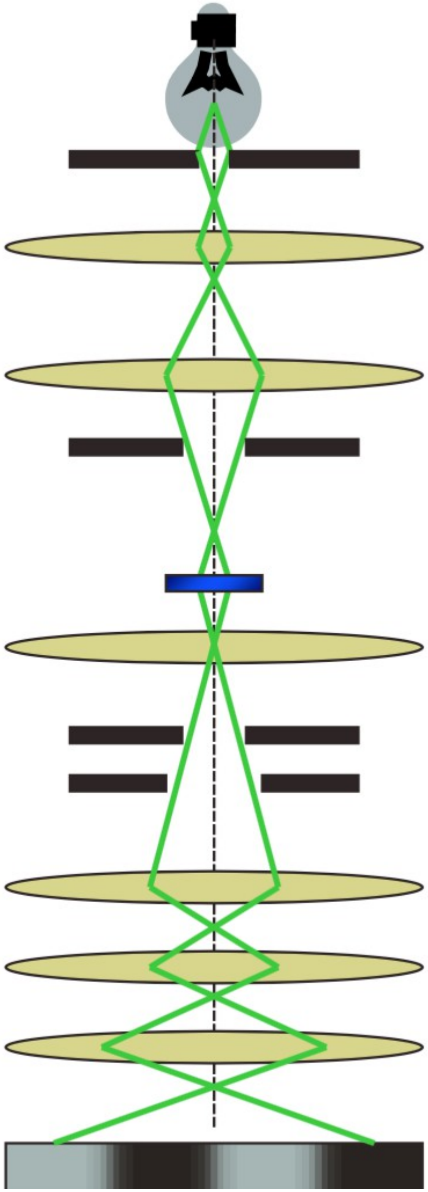
- Two main methods: magnetic analysis or ion time-of-fight
- Up to now other detector types in use, e.g. Multi Channel Plates for electron amplification followed by a suitable sensor, e.g. a pixel readout chip
- PImMS chip designed for detecting light from MCP/Phosphor layer
  - TOF-compatible
- Direct ion detection possible and could be advantageous, but ion range in detector limited, beware of dead surface layers





Electron Microscopy

Imaging in Transmission Electron Microscopy



Electron gun

Anode

Condenser aperture

Sample

Objective lens

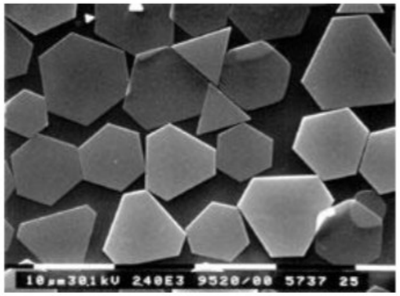
Apertures

Magnification and projection

Detector

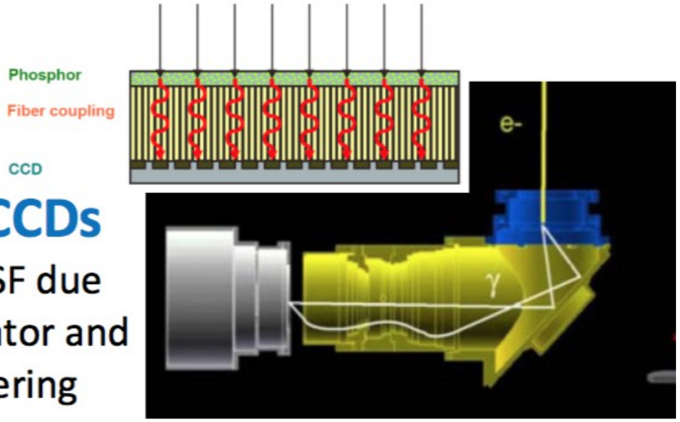
Film

- Large area
- High granularity
- Slow, no dynamic imaging



Optically Coupled CCDs

- Limited PSF due to scintillator and backscattering from optics



Direct Semiconductor Pixel Detectors

- High PSF and DQE from direct detection
- High speed readout
- Data processing capabilities

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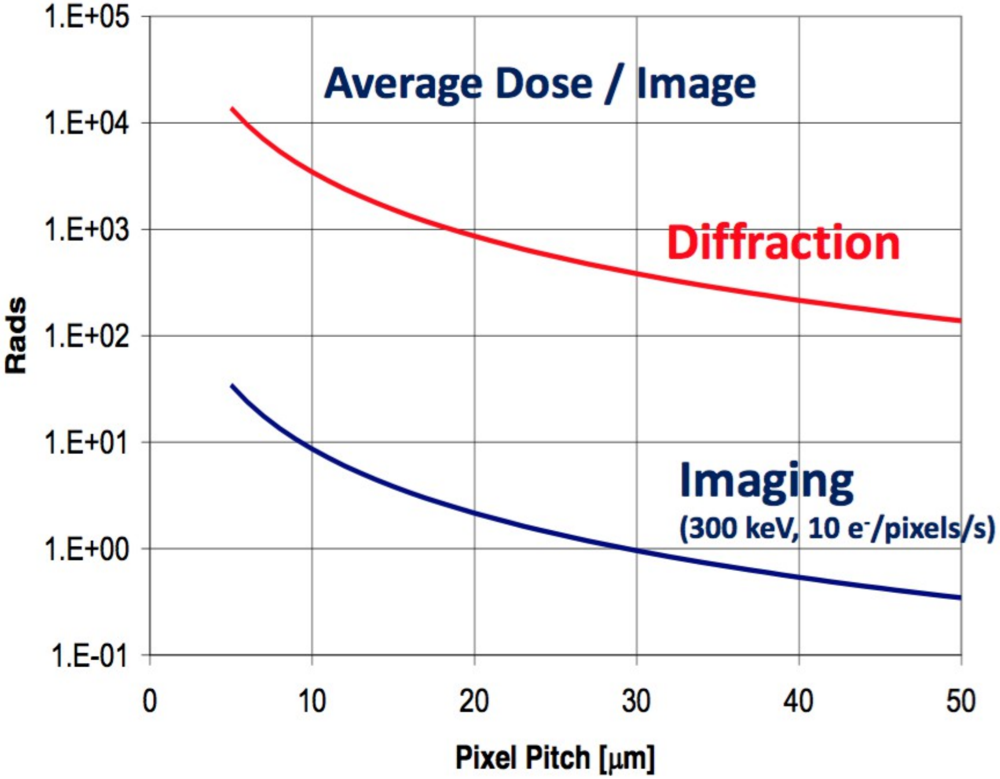
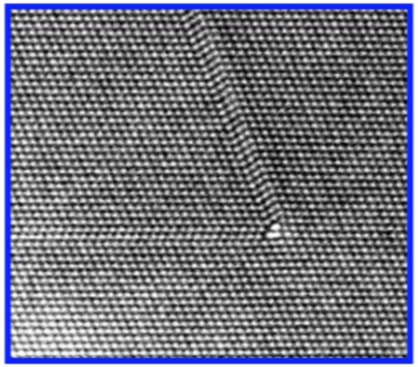
Electron Microscopy

Detector R&D Drivers: Radiation Hardness





- **Imaging mode**: O(1-10 Mrad) ionising dose expected for typical yearly usage (low dose conditions)
- **Diffraction mode**: very high doses localized in bright spots
- Radiation tolerance requirements comparable or worse than High Energy Physics applications → leverage extensive R&D on radiation tolerant design of sensors and readout electronics

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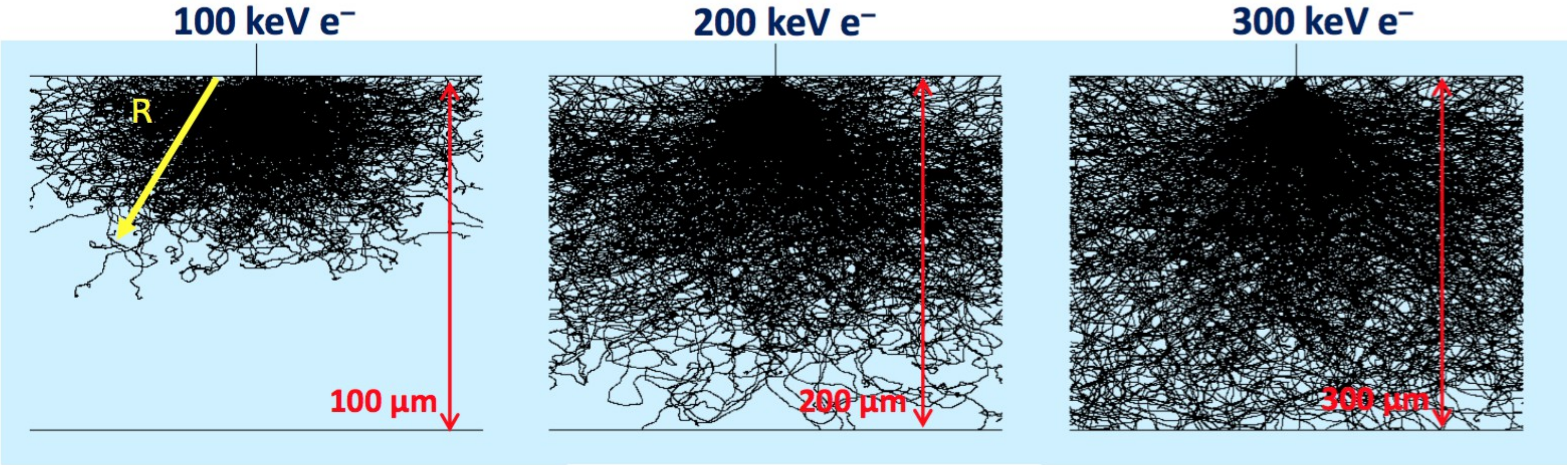
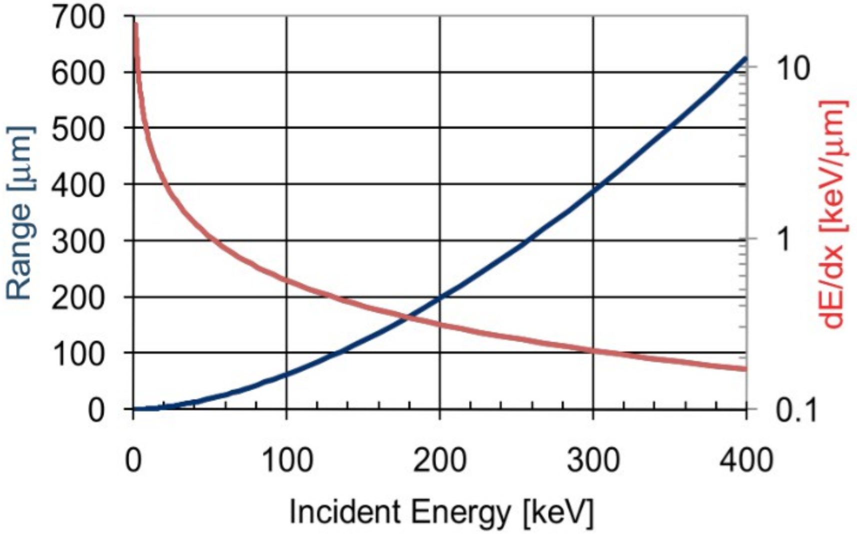
Detector R&D Drivers: Multiple Scattering





- Energies of interest to TEM: 80-400 keV
- Electron range **R [µm] ~ E [keV]**
- Energy loss **dE/dx ∝ 1/E**
- Need for a thin sensitive layer to minimize scattering contribution to Point Spread Function

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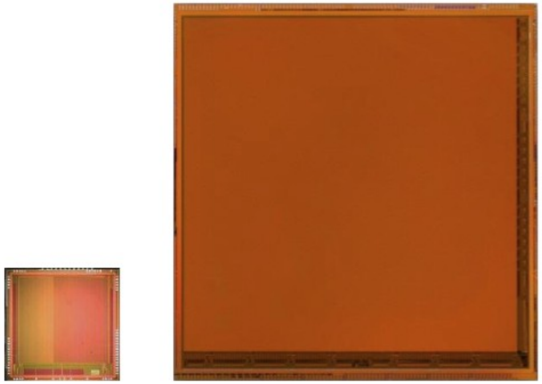
Electron Microscopy

Three Generations of CMOS APS for TEM Imaging

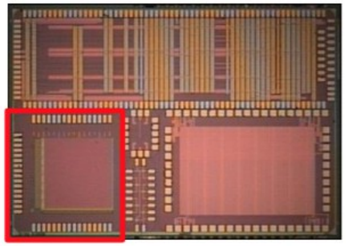
1st Generation (2008-2009)
0.35 µm CMOS → ams C35O
9.5 µm pixels
1 & 4 Mpixels
400 fps → 400 Mpixels/s
Imagers for the TEAM Project at NCEM

2nd Generation (2009-2011)
0.18 µm CMOS
5 µm pixels
16 MPixels
400 fps → 6400 Mpixels/s
Commercialized by Gatan, Inc.



http://www.gatan.com/K2/

3rd Generation (2011 – in progress)
65 nm CMOS
2.5 µm pixels
Prototype sensor under evaluation



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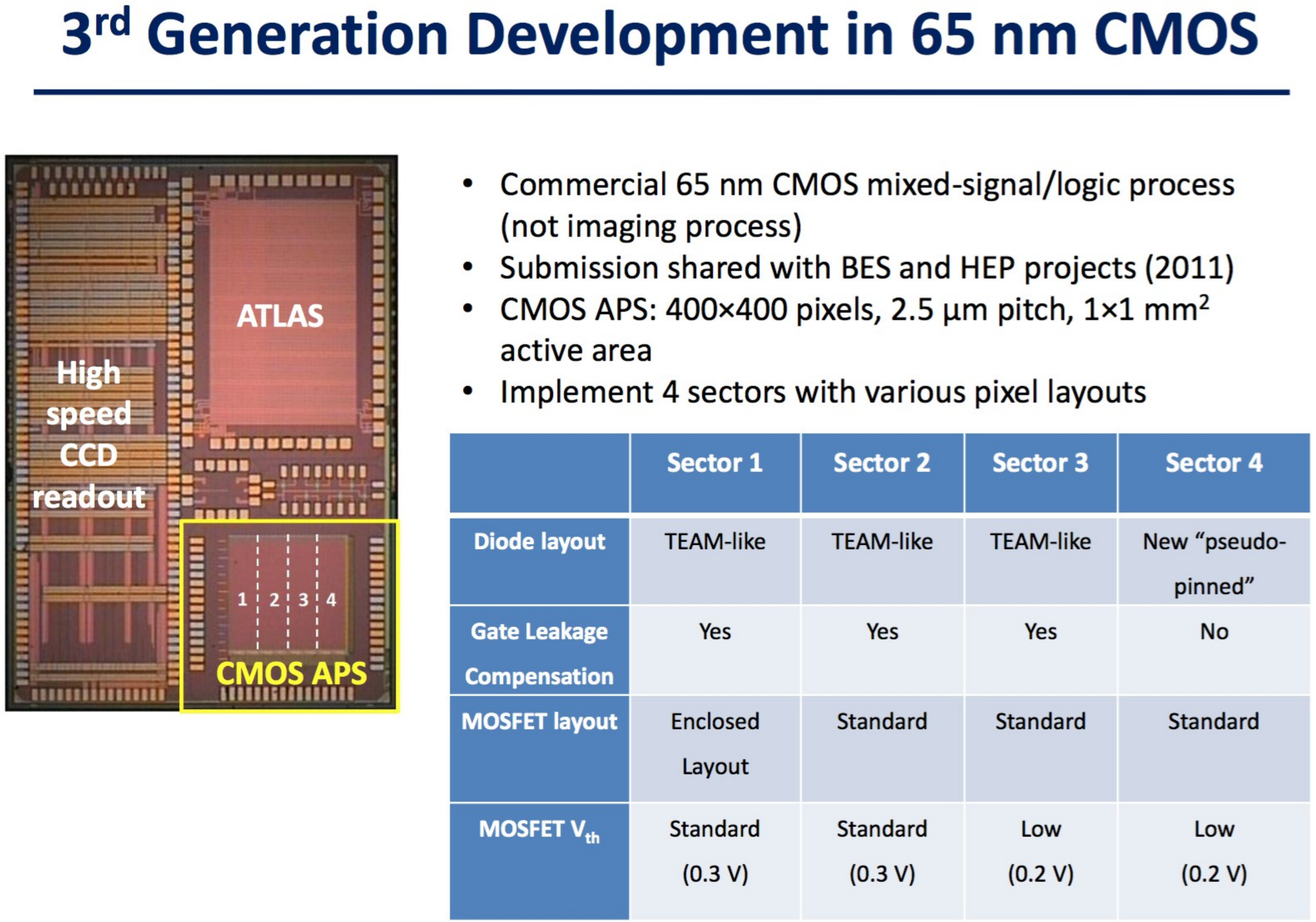
Charged Particle Detection

Electron Microscopy



3rd Generation Development in 65 nm CMOS

- Commercial 65 nm CMOS mixed-signal/logic process (not imaging process)
- Submission shared with BES and HEP projects (2011)
- CMOS APS: 400×400 pixels, 2.5 µm pitch, 1×1 mm^2 active area
- Implement 4 sectors with various pixel layouts

	Sector 1	Sector 2	Sector 3	Sector 4
Diode layout	TEAM-like	TEAM-like	TEAM-like	New “pseudo-pinned”
Gate Leakage Compensation	Yes	Yes	Yes	No
MOSFET layout	Enclosed Layout	Standard	Standard	Standard
MOSFET V_{th}	Standard (0.3 V)	Standard (0.3 V)	Low (0.2 V)	Low (0.2 V)

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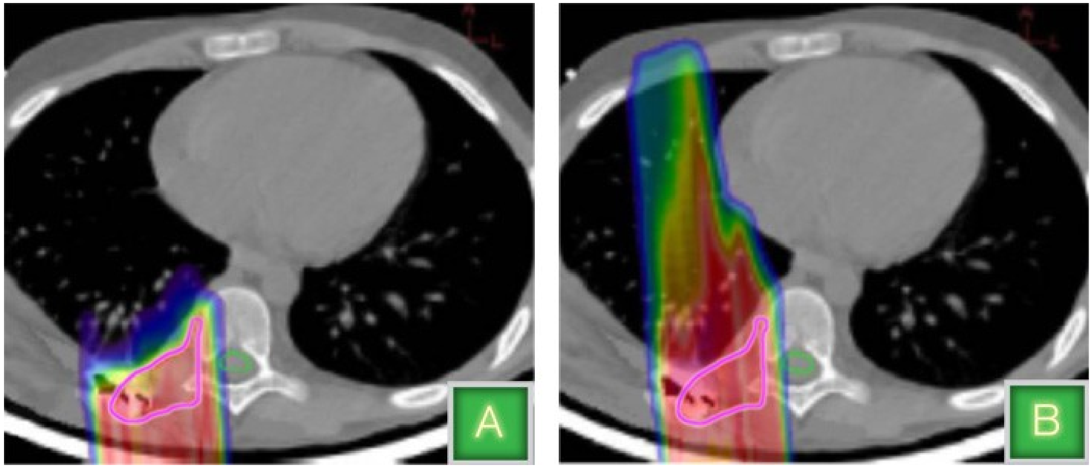
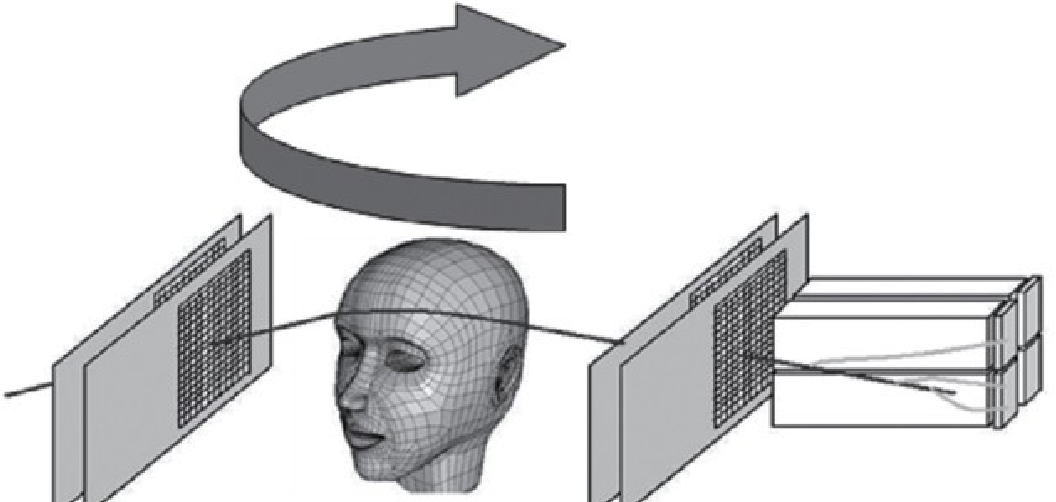
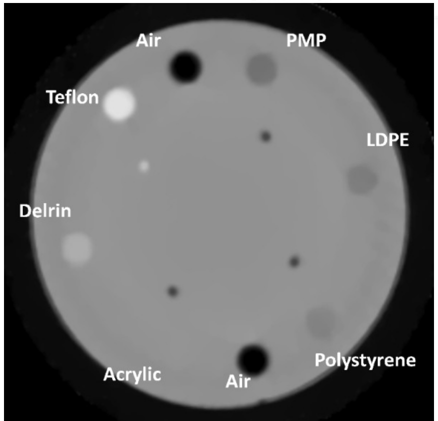
Medical applications: pCT

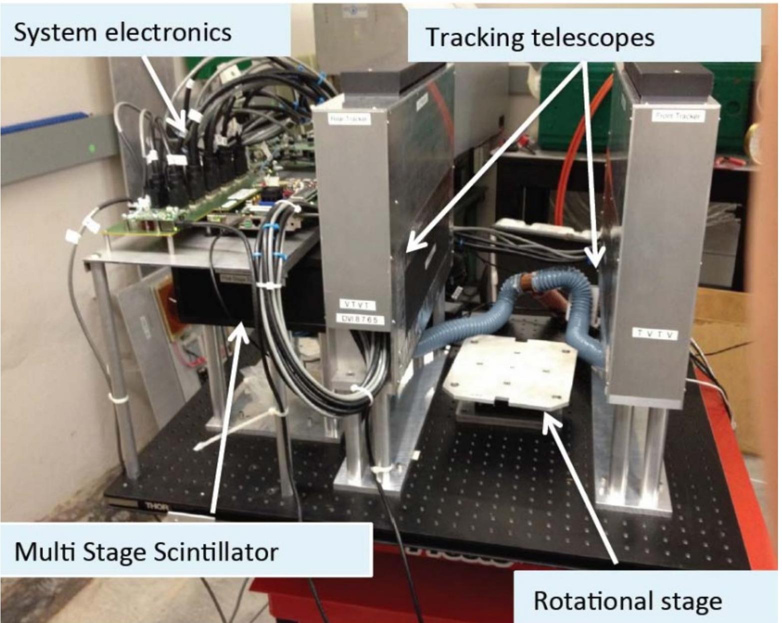
- Proton Computed Tomography is a CT method specifically suitable for proton/hadron therapy
  - standard CT measures electron densities, not mass densities required for precise hadron treatment planning
- Measure the scattering along each track followed by an energy measurement

E. Clements









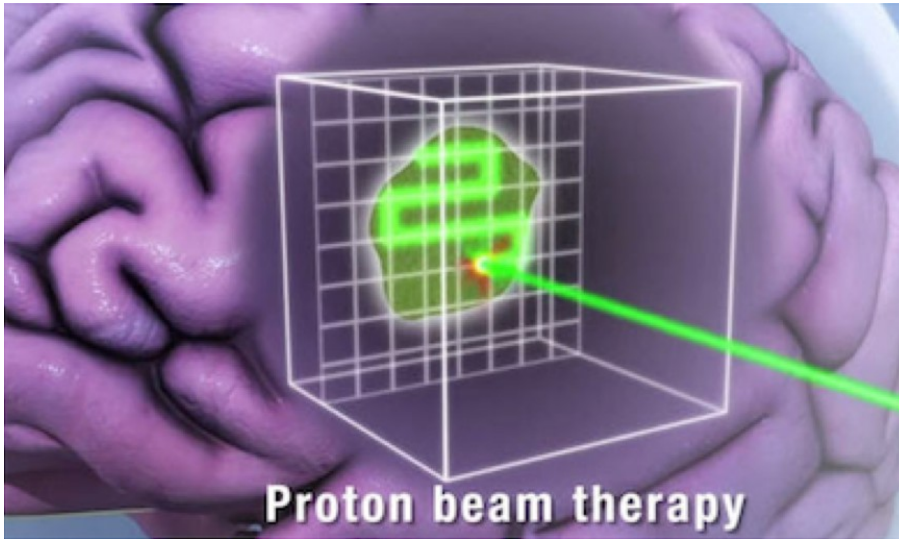
R. P. Johnson et al.

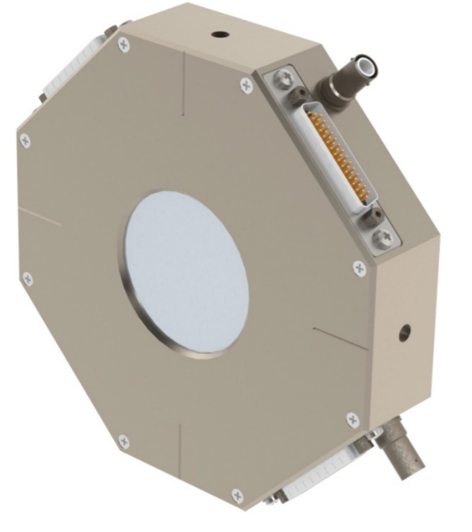
Medical applications: pCT

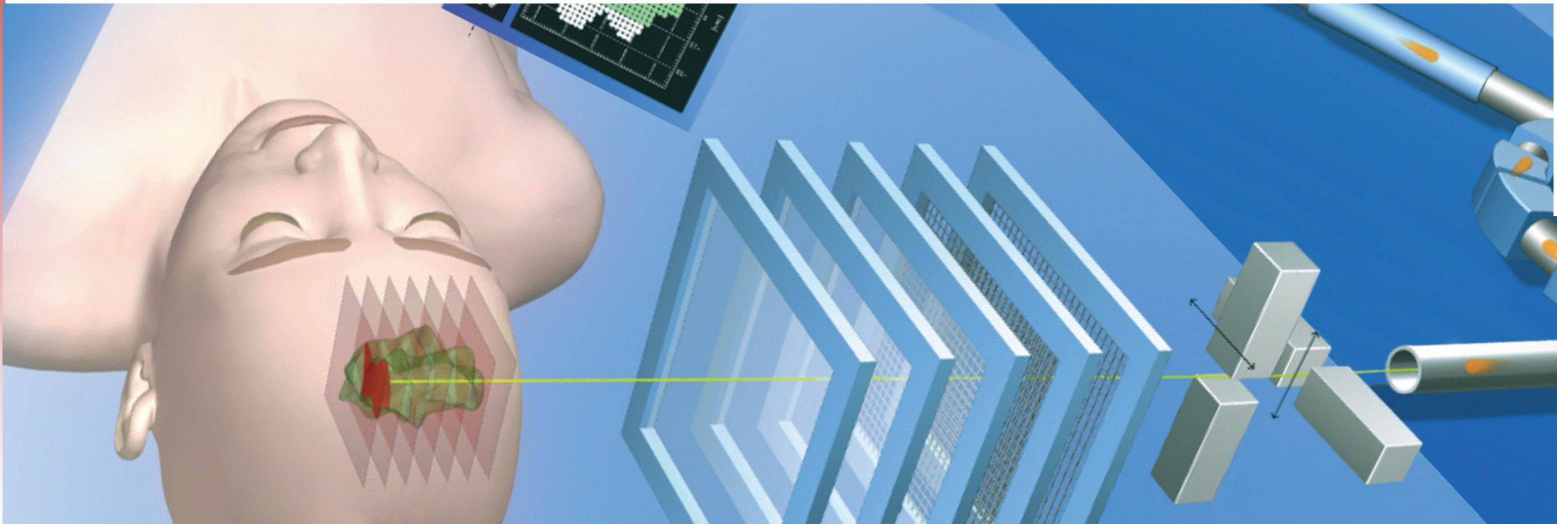
- Tracking sensors up to now
  - Silicon strip sensors
  - Fibre Trackers
  - GEMs
- CMOS detectors might be interesting candidates, in particular thanks to being able to being operated thin and giving both coordinates at the same time

Medical applications: particle therapy

- Particle Cancer Therapy requires stringent QA
  - regular (daily) control measurements of beam steering and energy calibrations
  - beam monitoring during treatment including feedback to beam steering
- Up to now done with stack of ionisation chambers
  - not individual particles, but mean current is measured
  - material budget important



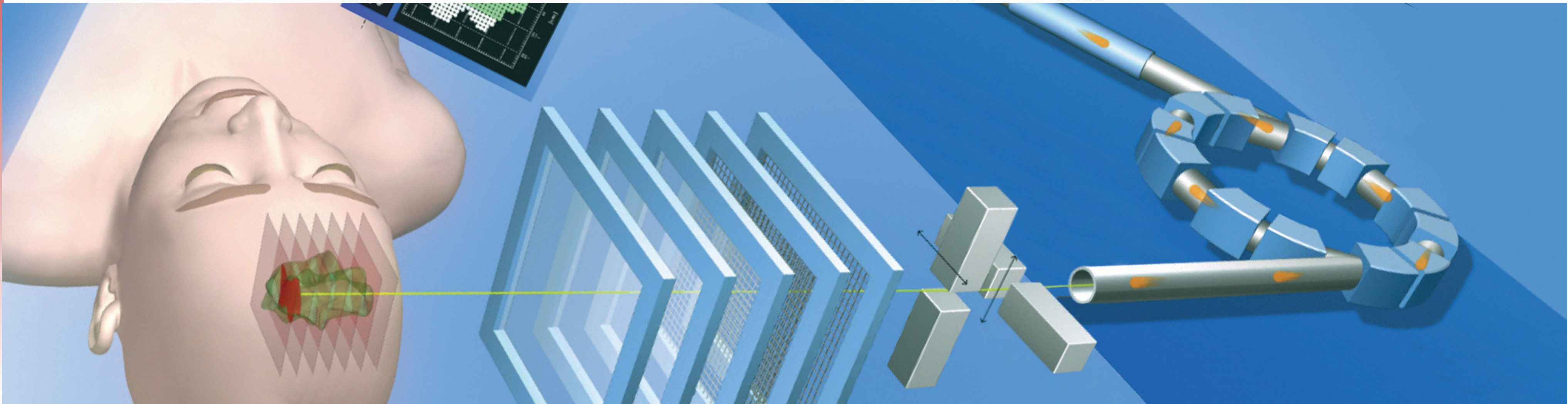




Medical applications: particle therapy

- CMOS detectors very good candidates for this application
  - radiation hard (1e9 protons/s with 1mm beam diameter)
  - high particle rates (ditto)
  - good resolution (currently: 500 µm beam mean)
  - fast readout (currently: 250 µm, is limiting scan speed)
  - low material budget (currently: 500 µm water equivalent → thinned devices)
  - even individual particle tracking might be an option

- Mobile detectors could also be applied to skin over entry ports or even body cavities
  - direct measurement of particle tracks, comparison to treatment planning



Conclusions

- CMOS sensors applicable to charged particle detection also outside of HEP tracker applications
- Many requirements rather relaxed compared to LHC environments
  - recycling of architechtures generally possible
  - potential issues:
    - high NRE costs for reticule-sized detectors
      - design towards versatility?
    - Large areas required, efficiency gaps sometimes an issue
      - very thin sensors with overlap?
      - stitching?
- Major issues:
  - (lack of) chip designers in several communities
  - comparatively high initial investment (both monetary and know-how wise) compared to established technologies