Fall School of the IRTG "Development and Application of Intelligent Detectors"
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Introduction to Silicon Detectors and Radiation Damage

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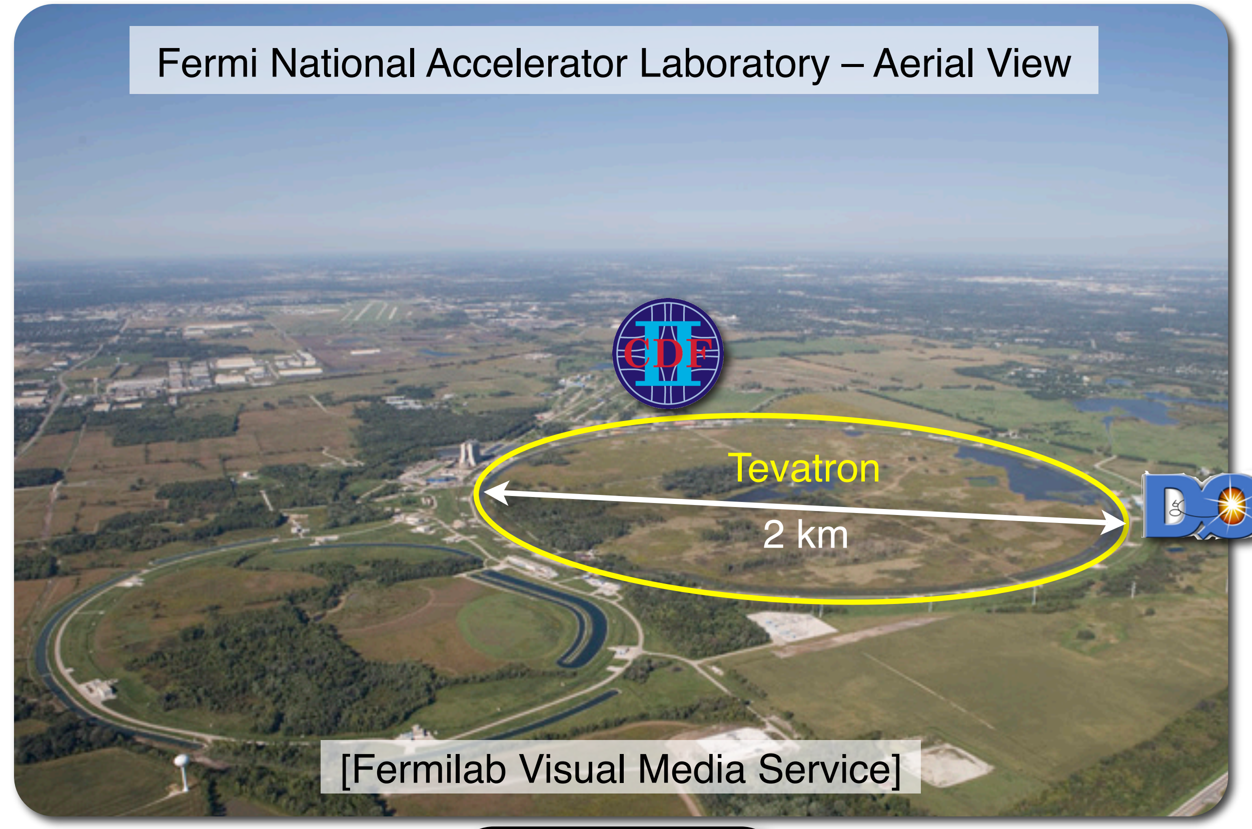
Introductory Lectures: Outline

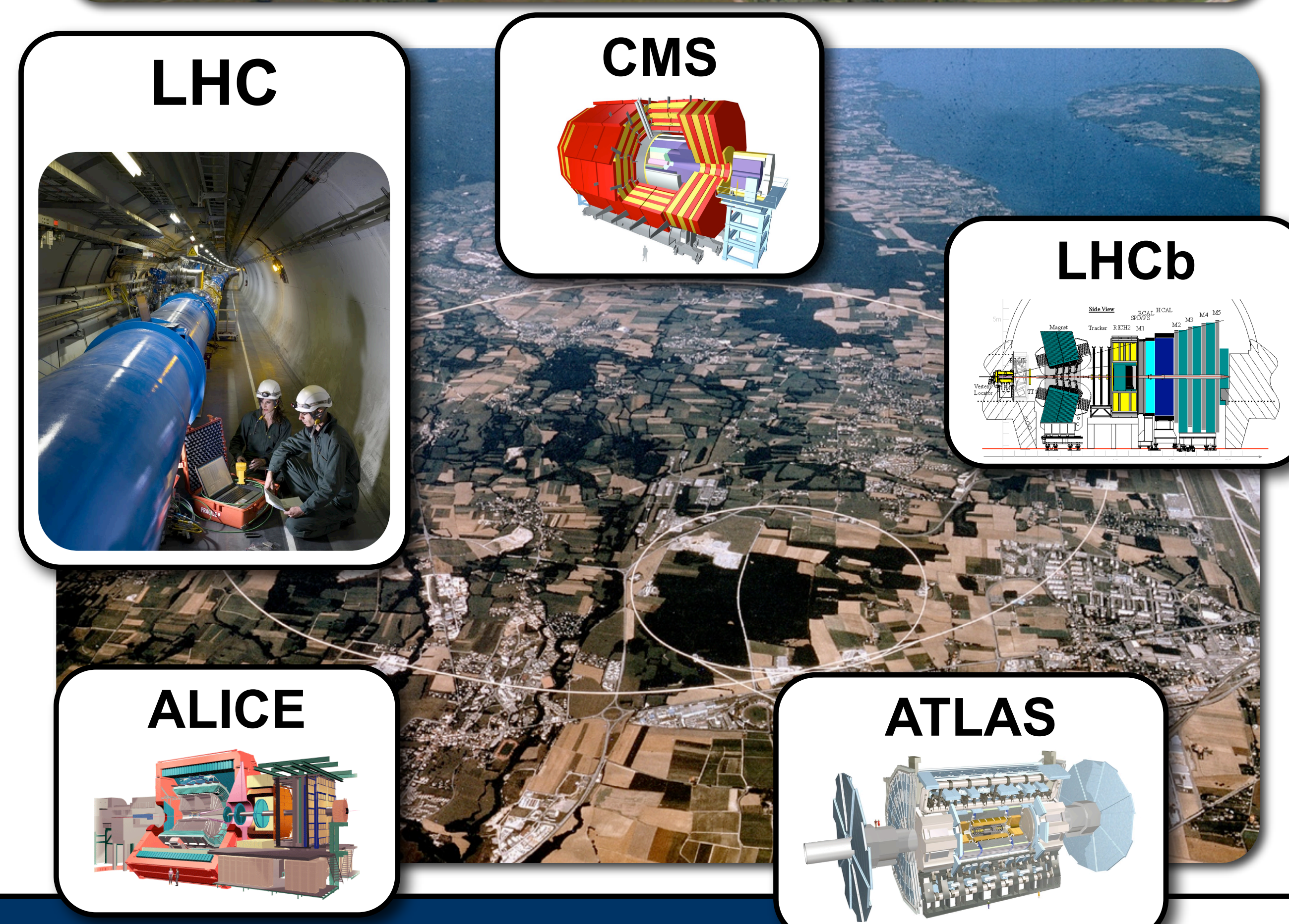
- Introduction
  - How and where are silicon detectors employed at hadron colliders?
  - Which detector components suffer from radiation damage?
- Part I: Radiation Damage in Silicon Sensors (UH)
  - What are typical sensor defects caused by radiation?
  - Which operational parameters are affected?
  - How can radiation damage be measured in the lab and how can it be modeled?
- Part II: Radiation Damage in Silicon Readout Electronics (Ketil Røed)
  - What is radiation environment responsible for inducing single event upsets (SEUs) in FPGAs?
  - How do SEUs affect SRAM memory cells and FPGAs?
  - How can SEU failures be tested, predicted, and reduced?

Introduction

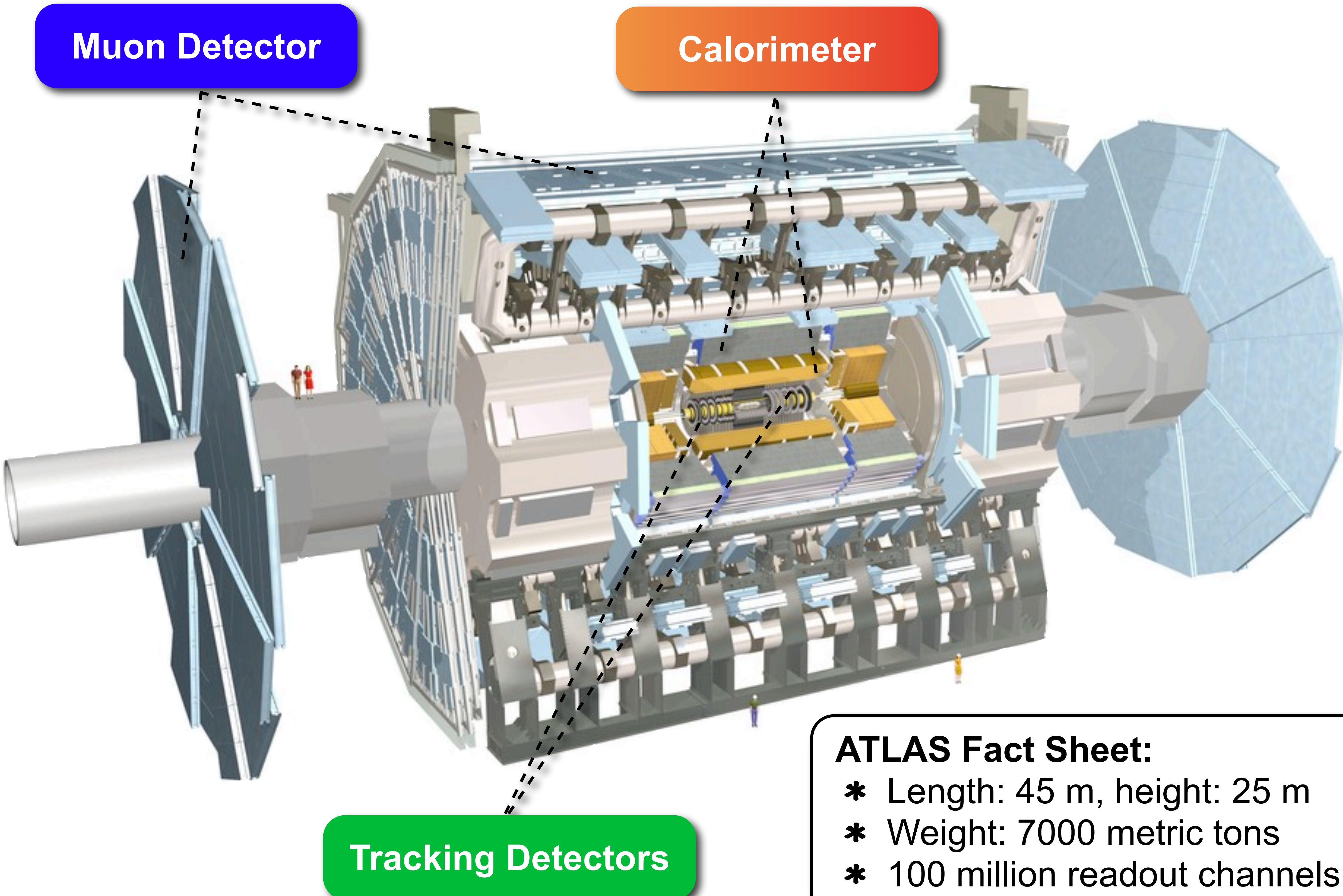
Hadron Collider Experiments

- Silicon detectors employed in many particle physics experiments
  - Fixed target
  - Hadron colliders
  - Lepton and ep colliders,
- … and for various purposes
  - Charged particle tracking & vertexing
  - Calorimetry
- This lecture: restricted to silicon-based tracking and vertexing detectors at hadron colliders, e.g.
  - Sp$\bar{p}$S: p$\bar{p}$ at $\sqrt{s}$ = 630 GeV
  - Tevatron: p$\bar{p}$ at $\sqrt{s}$ = 1.8–1.96 TeV
  - LHC: pp at $\sqrt{s}$ = 7–14 TeV





Detector Example: ATLAS



ATLAS Fact Sheet:

- Length: 45 m, height: 25 m
- Weight: 7000 metric tons
- 100 million readout channels

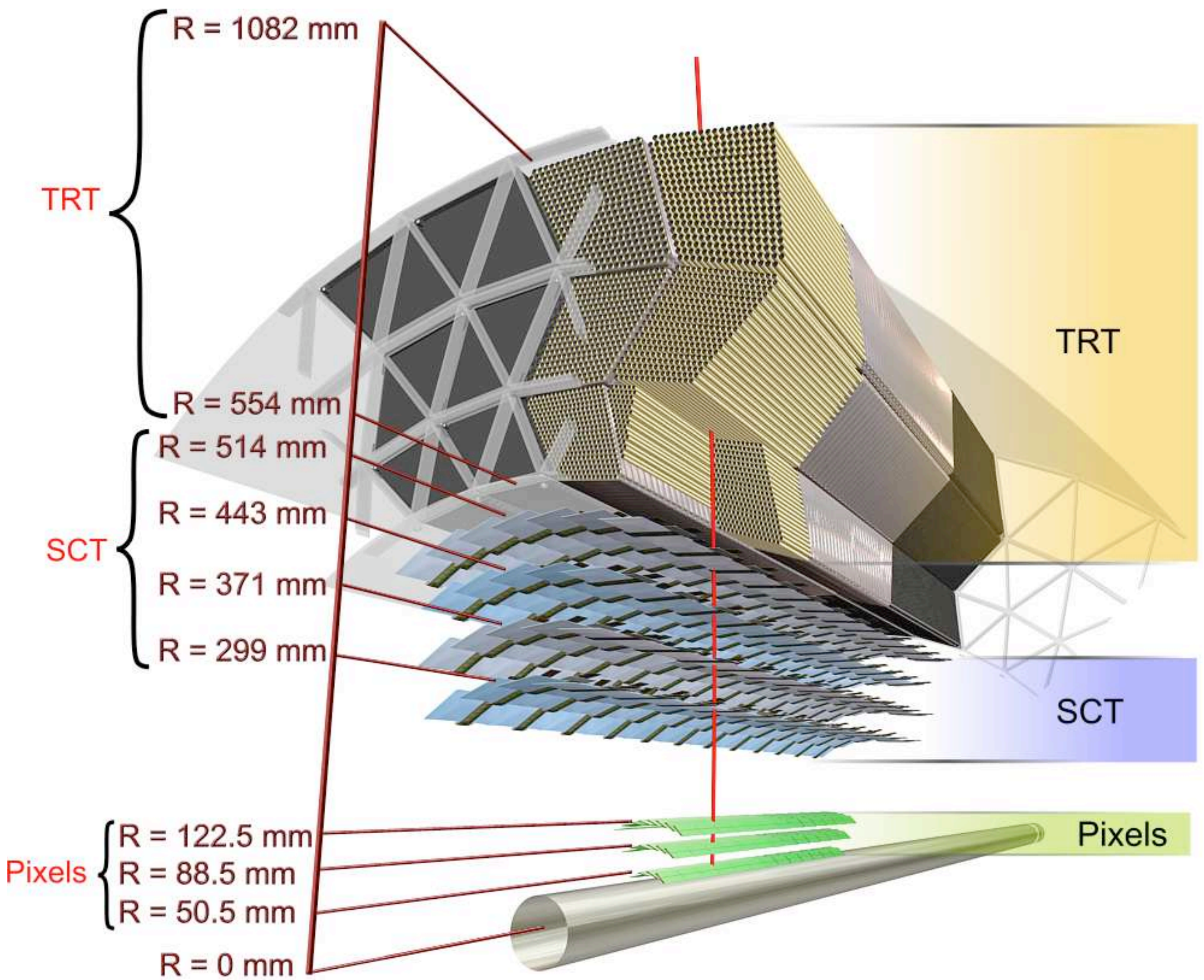
LHC Tracking & Vertexing Challenges

- Physics goals: find (something like) the Higgs and/or New Physics
  - Production cross sections expected to be small (fb)
  - Need high instantaneous luminosity (now: 2×10^{32} cm^{-2} s^{-1}, design 10^{34} cm^{-2} s^{-1})
- Tracking detector requirements are a challenge
  - High bunch crossing rate (40 MHz) → fast readout electronicss
  - Large flux of charged and neutral particles per collision → highly granular detectors to keep channel occupancies below 1–2%
  - Many physics signature (e.g. tagging of *b*-quark jets) require excellent vertexing → transverse impact parameter resolution better than 15 μm
  - Particle production in hadronic interactions: lots of hadrons produced (pions, kaons, protons, neutrons, …) → radiation hard detectors and electronics (>100 kGy/year)
- Tracking detector technology of choice at the LHC
  - Small radial distance from beam pipe (<20 cm): silicon pixel detectors
  - Larger radial distance: silicon microstrip detectors

The ATLAS Inner Detector

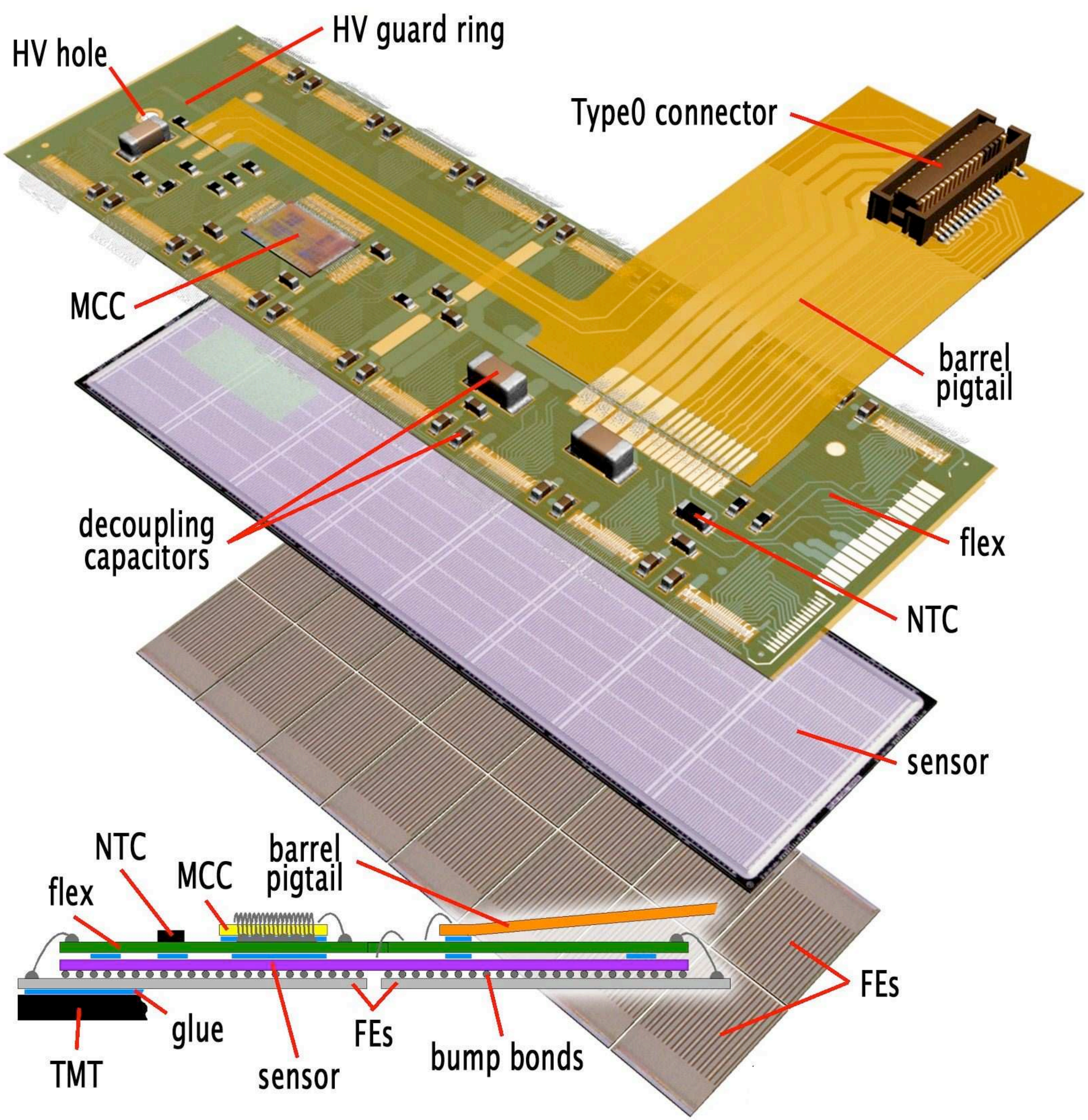
- Transition Radiation Tracker (TRT)
  - 350,000 straw drift tubes
  - Transition radiation for e/π separation
- Semiconductor Tracker (SCT)
  - Strip pitch: 80 μm
  - 6.3 million readout channels
- Silicon Pixel Detector
  - Pixel size: 400×50 μm^2
  - 80 million readout channel
  - Innermost layer: 50.5 mm from beam

Slice of ATLAS Inner Detector Barrel



[2008 JINST 3 S08003]

ATLAS Pixel Module



[2008 JINST 3 S08003]

- Typical hybrid pixel module built of
  - Readout “flex” hybrid
  - Sensor: 46k pixels
  - 16 front-end (FE) chips
- Lots of electrical connections
  - FE chips bump-bonded to sensor, wire-bonded to flex
  - In: chip and sensor power (low and high voltage), chip commands, trigger
  - Out: digitized data (later transformed into optical)
- Cooling system (not shown): remove heat dissipated by FE chips

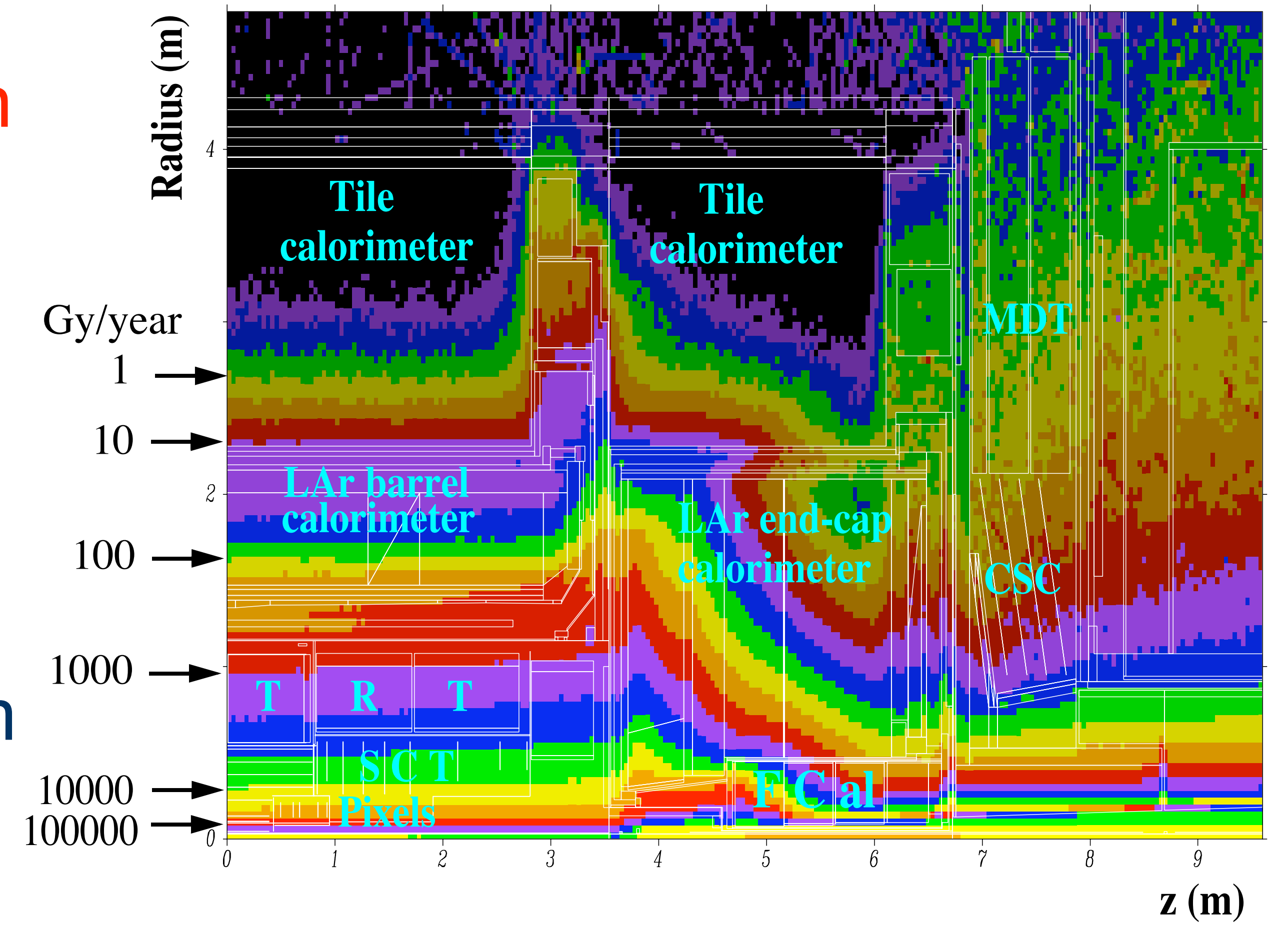
ATLAS Expected Radiation Field

- Most forms of radiation damage characterized by ionizing radiation dose rate (in gray/year)
- More relevant for silicon detectors: fluence Φ (in cm^{-2})

$$\Phi = \int \phi(E)\,\mathrm{d}E$$

with $\phi(E)$ particle energy spectrum (normalized to 1 MeV neutrons)

ATLAS Total Ionizing Dose Rate



[ATLAS, 2008 JINST 3 S08003]

Region	R (cm)	Particle rates (kHz/cm^2)						F_{neq}	Ionisation
		γ	Protons	Neutrons	$\pi^\pm$	$\mu^\pm$	e^-	($\times 10^{+12}$ cm^{-2})	dose (Gy/y)
		$>$ 30 keV	$>$ 10 MeV	$>$ 100 keV	$>$ 10 MeV	$>$ 10 MeV	$>$ 0.5 MeV		
Pixel layer 0	5.05	45800	2030	4140	34100	300	8140	270	158000
Pixel layer 2	12.25	9150	280	1240	4120	190	1730	46	25400
SCT barrel layer 1	29.9	4400	80	690	990	130	690	16	7590
SCT barrel layer 4	51.4	3910	36	490	370	67	320	9	2960
SCT end-cap disk 9	43.9	7580	73	840	550	110	470	14	4510
TRT outer radius	108.0	2430	10	380	61	7	53	5	680

Compare ISS: < 0.1 Gy/y

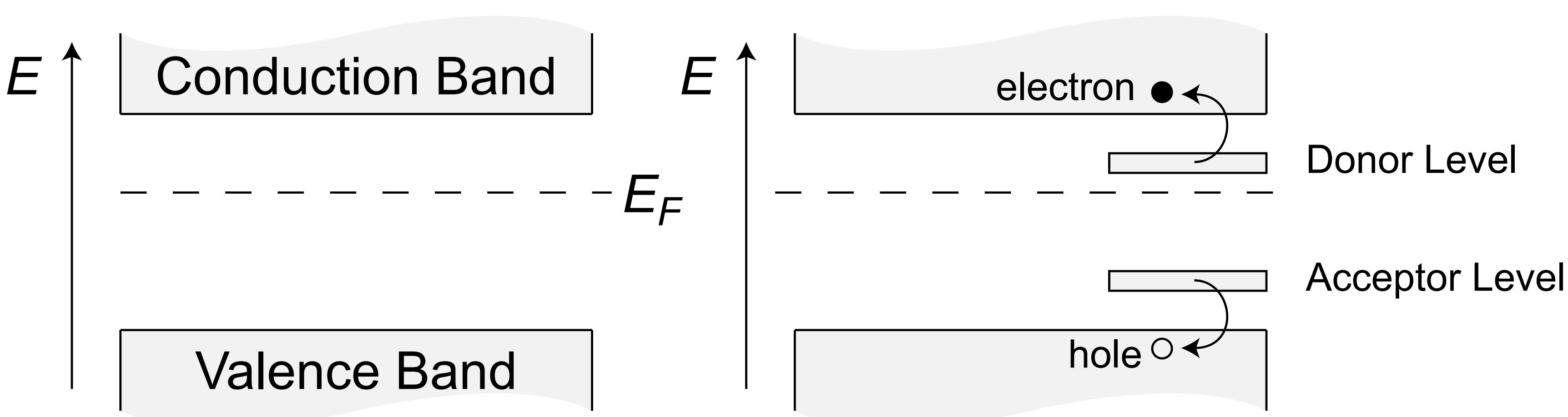
Radiation Damage in a Silicon Detector

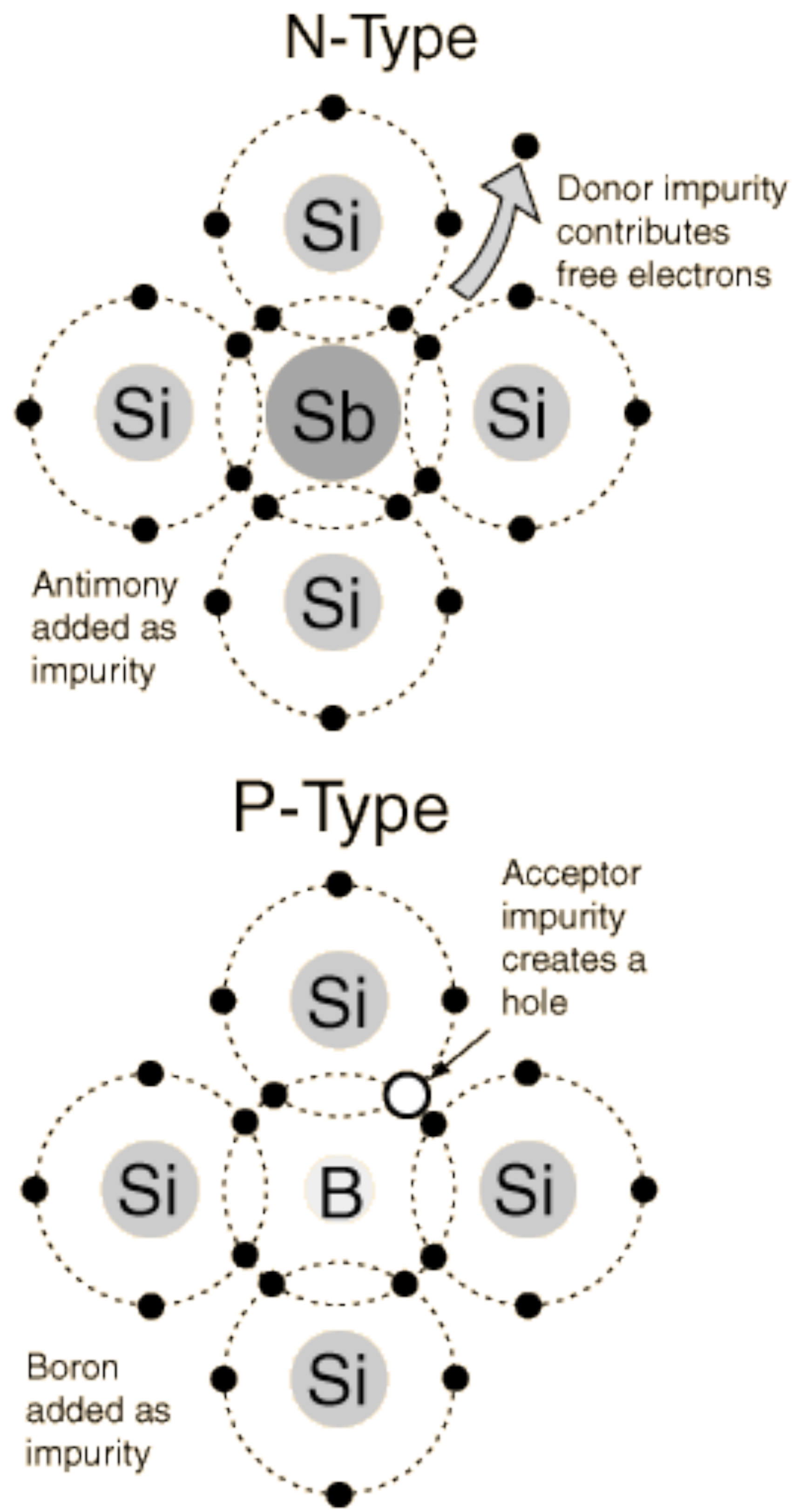
- Radiation influences all detector components in experimental hall
  - Detector modules: sensors, readout chips, control chips
  - Parts of readout chain (electrical & optical data transmission)
  - Parts of infrastructure in experimental hall: cooling system, power supplies/ converters
- In general: damage depends on composition of radiation field
  - Charged leptons and hadrons: large penetration, secondary interactions in material
  - Photons: photo-effect, Compton effect, pair production
  - Neutrons: hard to shield, low-energy neutrons wander through hall “out of time”
  - Composition of radiation field changes with distance from collision point, e.g. damage to ATLAS pixel detector dominated by charged hadrons (>85%), but 50% of SCT damage caused by neutrons
- This pair of introductory lectures;
  - Part I: Radiation damage in silicon sensors
  - Part II: Radiation damage in electronics, especially FPGAs

Part I: Radiation Damage in Silicon Sensors

Doped Semiconductors

- Pure silicon is a semiconductor
  - Band model: valence and conduction bands
  - Band gap in silicon: 1.12 eV
  - Fermi level (at 0 K) inside band gap, conductivity through thermal excitations
- Properties can be changed by doping
  - Additional energy levels in band gap
  - Donors: creation of additional electrons
  - Acceptors: creation of additional holes

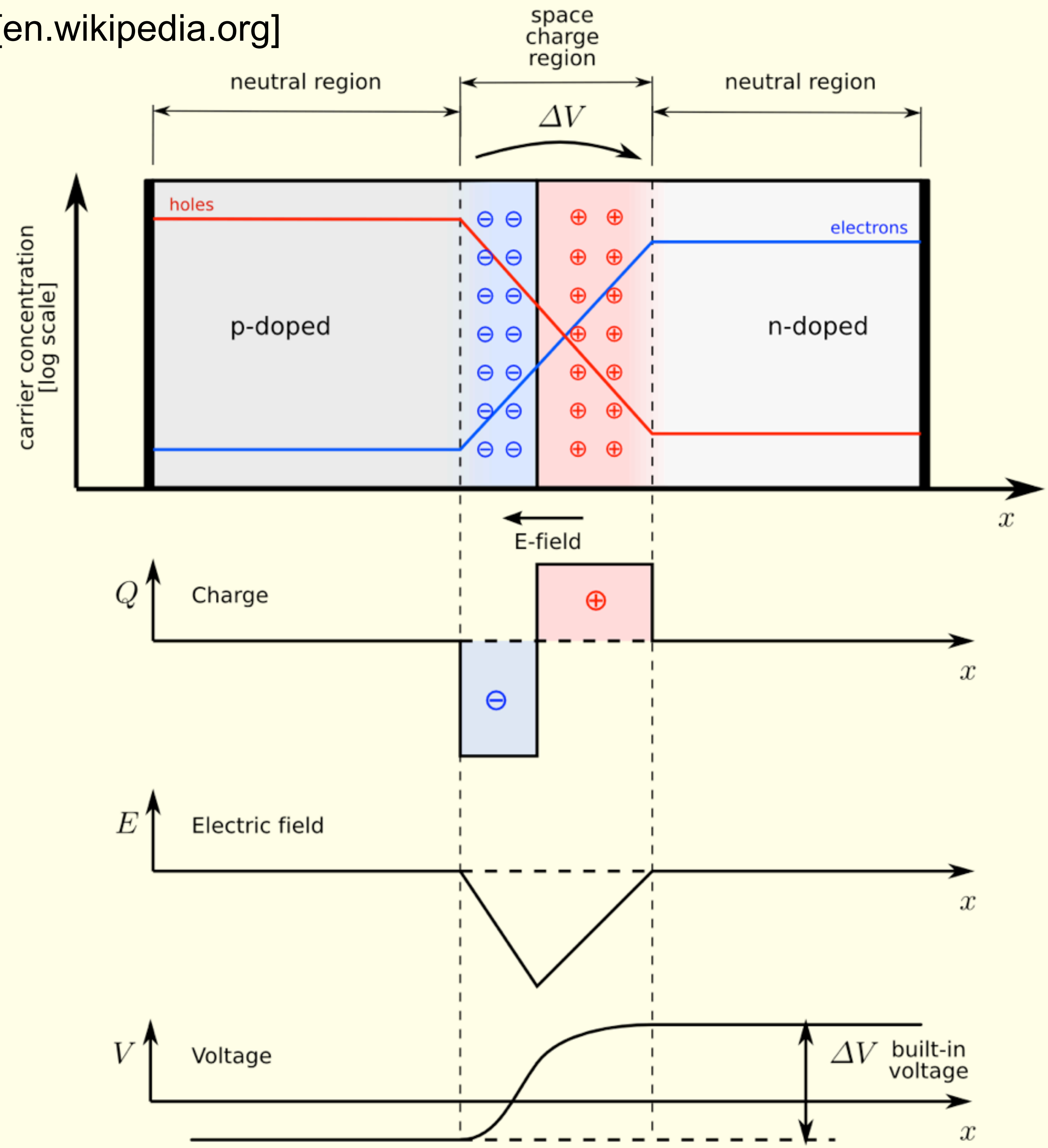




[hyperphysics.phy-astr.gsu.edu]

Semiconductor Diodes

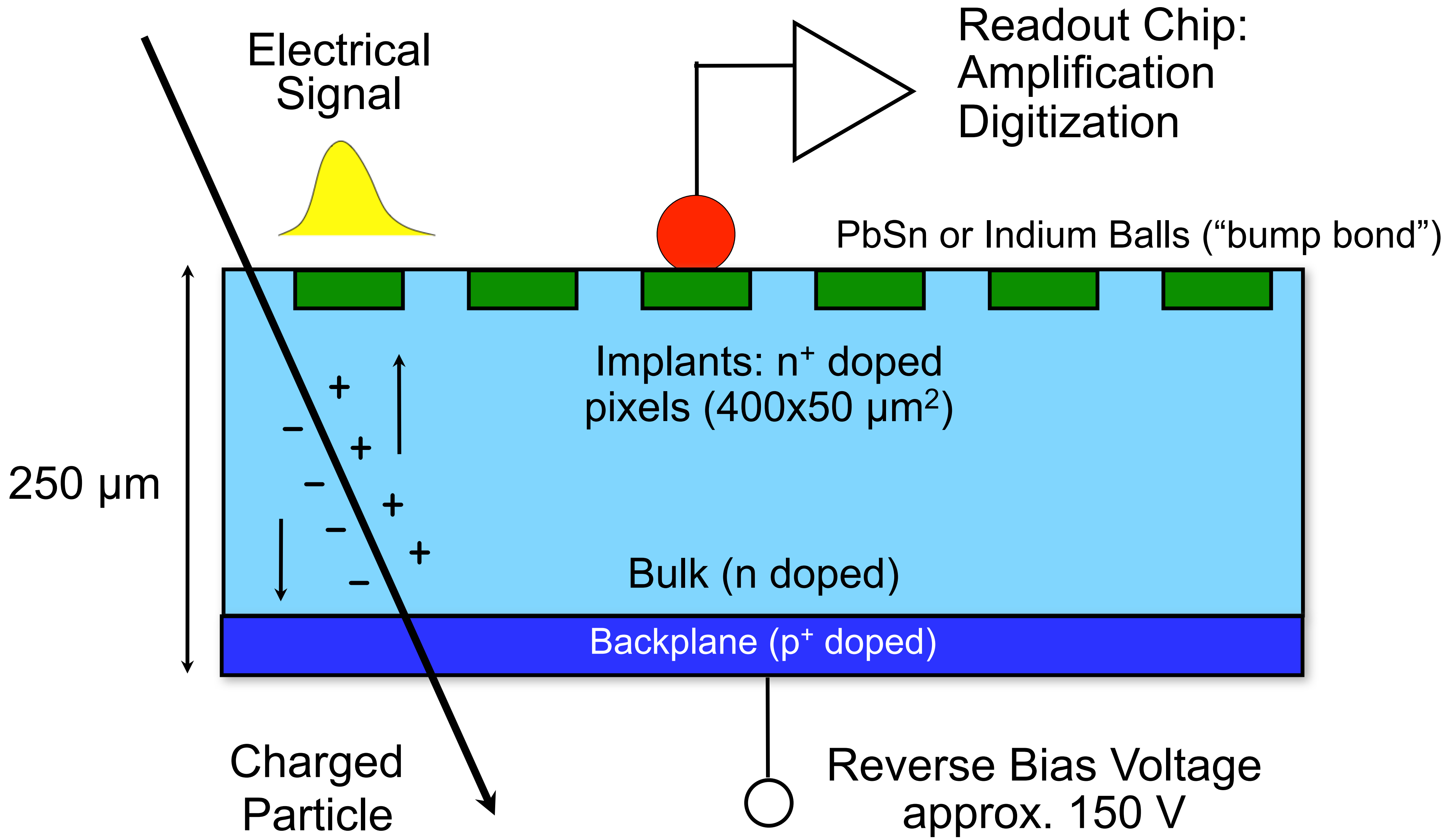
[en.wikipedia.org]



- Diode = interface of p-doped and n-doped semiconductors:
  - Electrons and holes re-combine → depletion zone
  - Reverse bias voltage applied → depletion zone extended

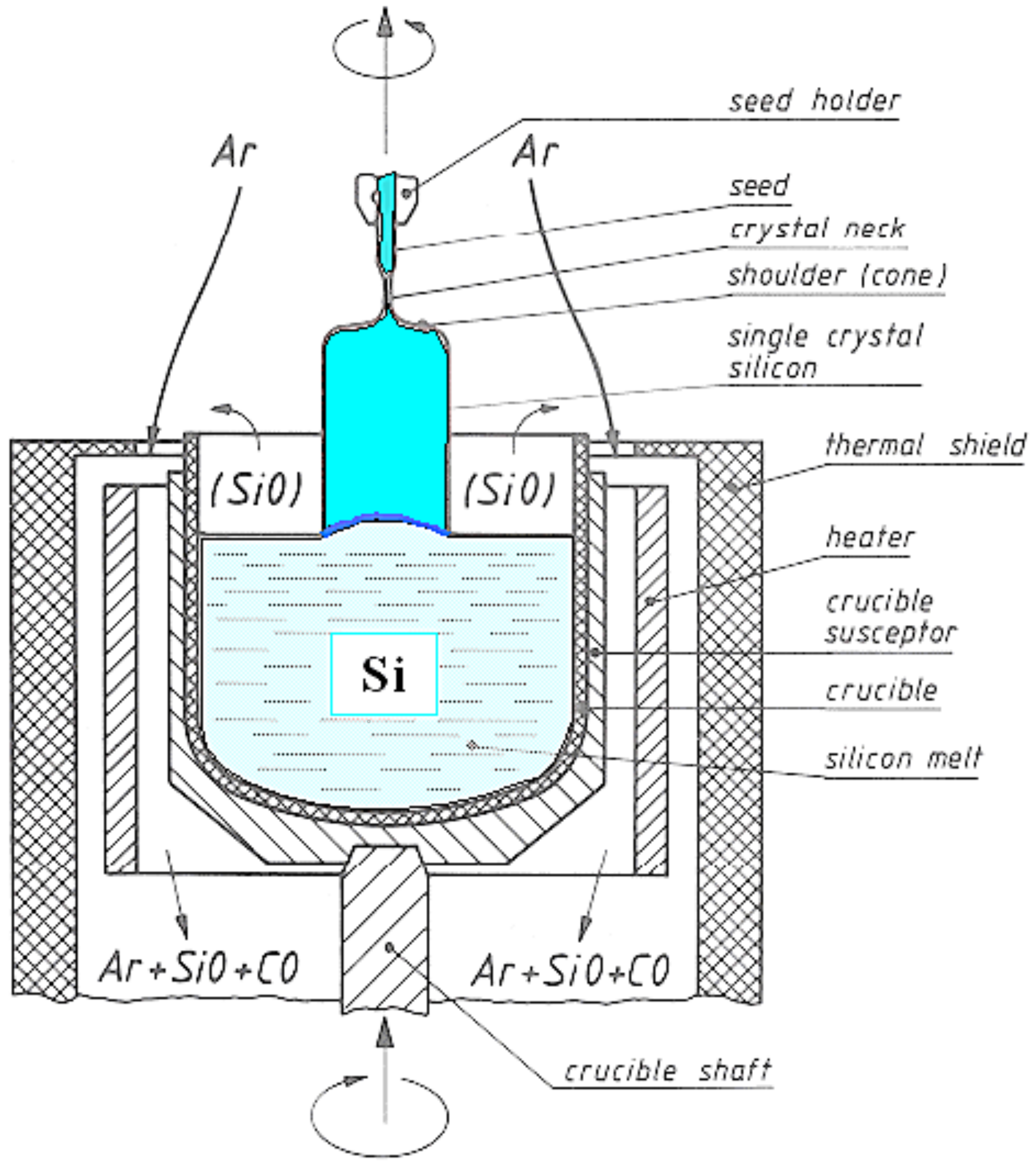
Silicon Detectors at a Glance

- Example: hybrid pixel detectors
  - Detector = semiconductor diode with pn junction in reverse bias → depletion zone
  - Charged particles ionize detector material → electron/hole pairs induce signal

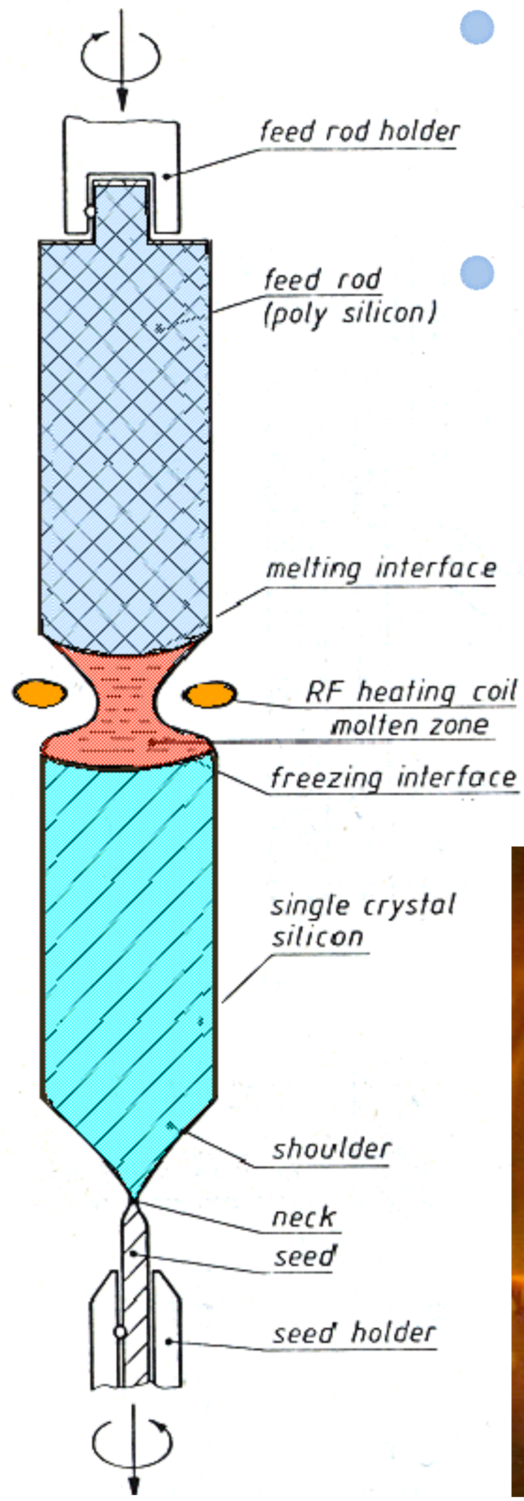


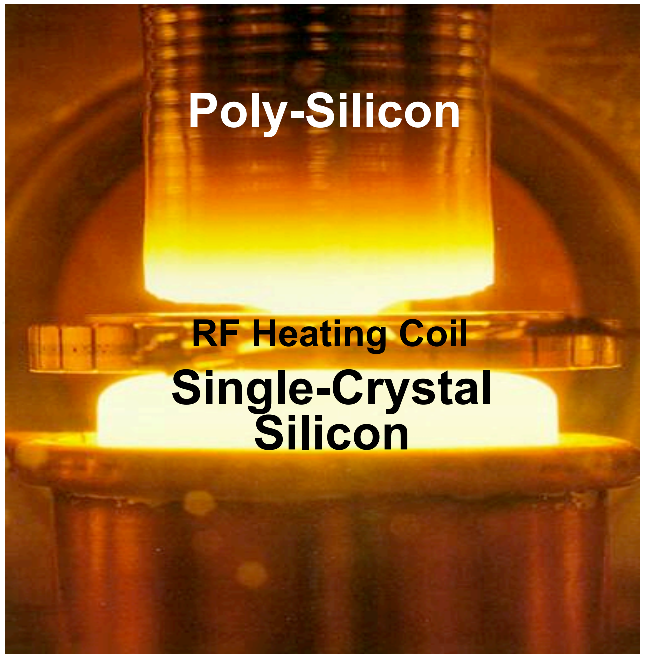
Silicon Production Mechanisms

- Czochralski (Cz) silicon:
  - Mono-crystal pulled out of silicon melt
  - Cheap (standard for microelectronics) but low purity (e.g. high oxygen concentration)



- Float Zone (FZ) silicon:
  - Polycrystalline rod melted into mono-crystal
  - High purity but expensive



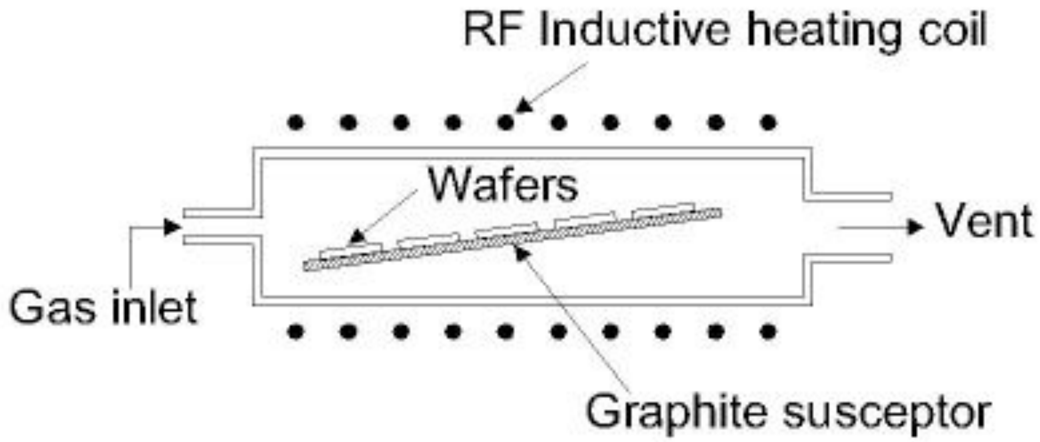


Detector Grade Silicon

- Requirements for particle detectors:
  - Very high resistivity: > 1 kΩcm → allows full depletion of 300 μm thick sensor with 300 V
  - High purity: low noise
  - Crystal orientations: 〈111〉 〈100〉
- Refinements of production methods:
  - MCz: magnetic field controls convection in melt → more homogeneous than Cz, lower oxygen concentration
  - DOFZ: diffusion oxygenated FZ silicon → oxygen-enriched: believed to be beneficial for radiation hardness
  - Epitaxial (EPI) silicon: silicon in vapor phase (e.g. $SiCl_4$) deposited on substrate

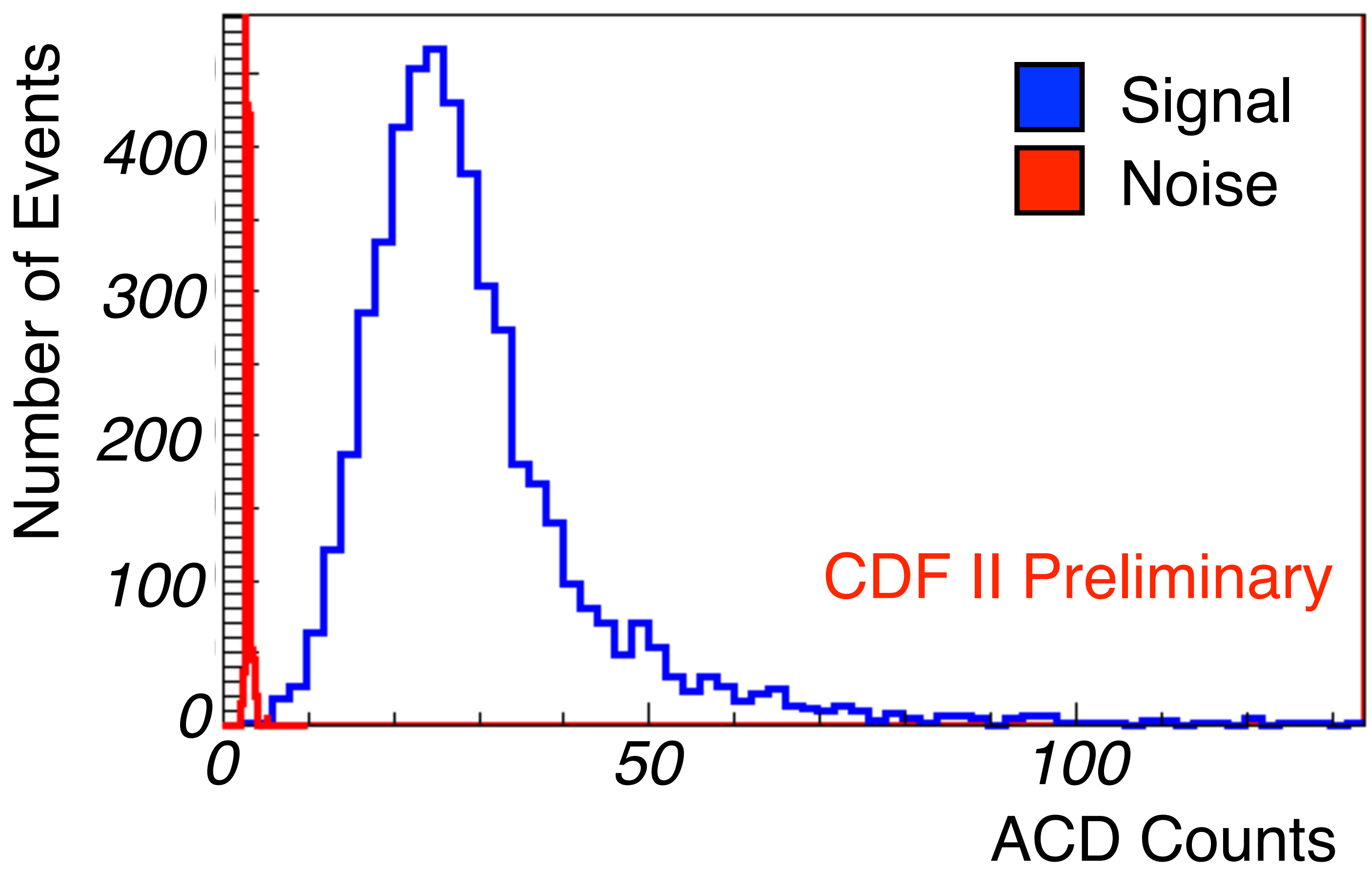
Silicon Ingots and Wafers

Epitaxy



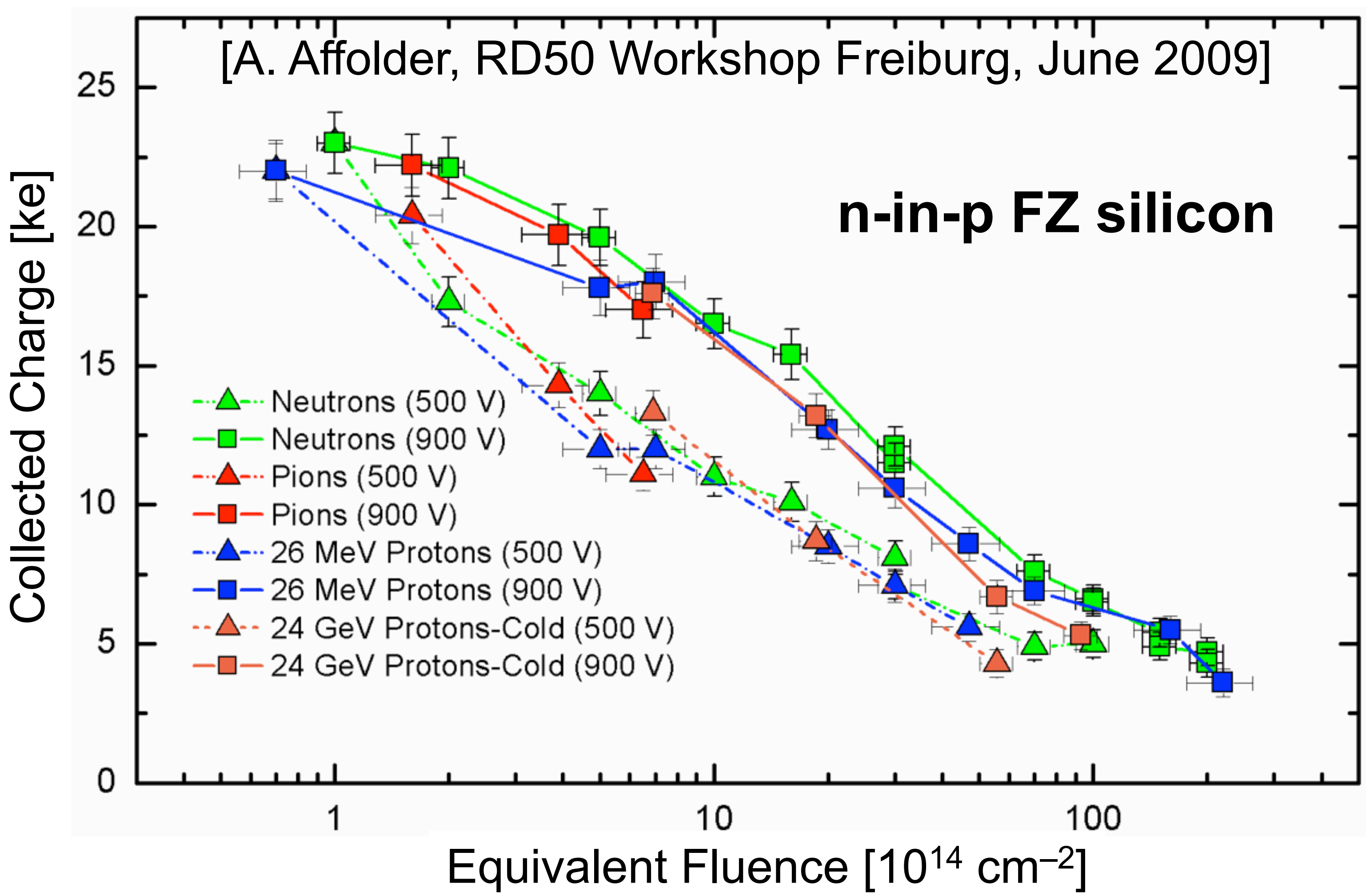
Radiation & Performance Parameters

- Single hit resolution dominated by strip pitch or pixel size (plus improvements from charge sharing) → usually not affected by radiation
- Signal-to-noise ratio (S/N): various radiation effects
  - Large values desirable: S/N > 15–20
  - Rule of thumb: problems for pattern recognition for S/N < 6
    → many wrong track seeds formed from combinations of signal and noise hits



Charge Collection Efficiency

- Charge collection efficiency (CCE)
  - Ionization required to create one electron/hole pair: 3.6 eV
  - Energy loss via ionization in silicon: d*E*/d*x* of a MIP 3.88 MeV/cm (mean)
  - Typical signal in 300 μm thick silicon bulk (using most probable energy loss = 0.7×mean) 22500 electrons = 3.6 fC
  - Radiation damage mechanism: trapping of parts of the electrons in sensor defects (details later) → smaller signal



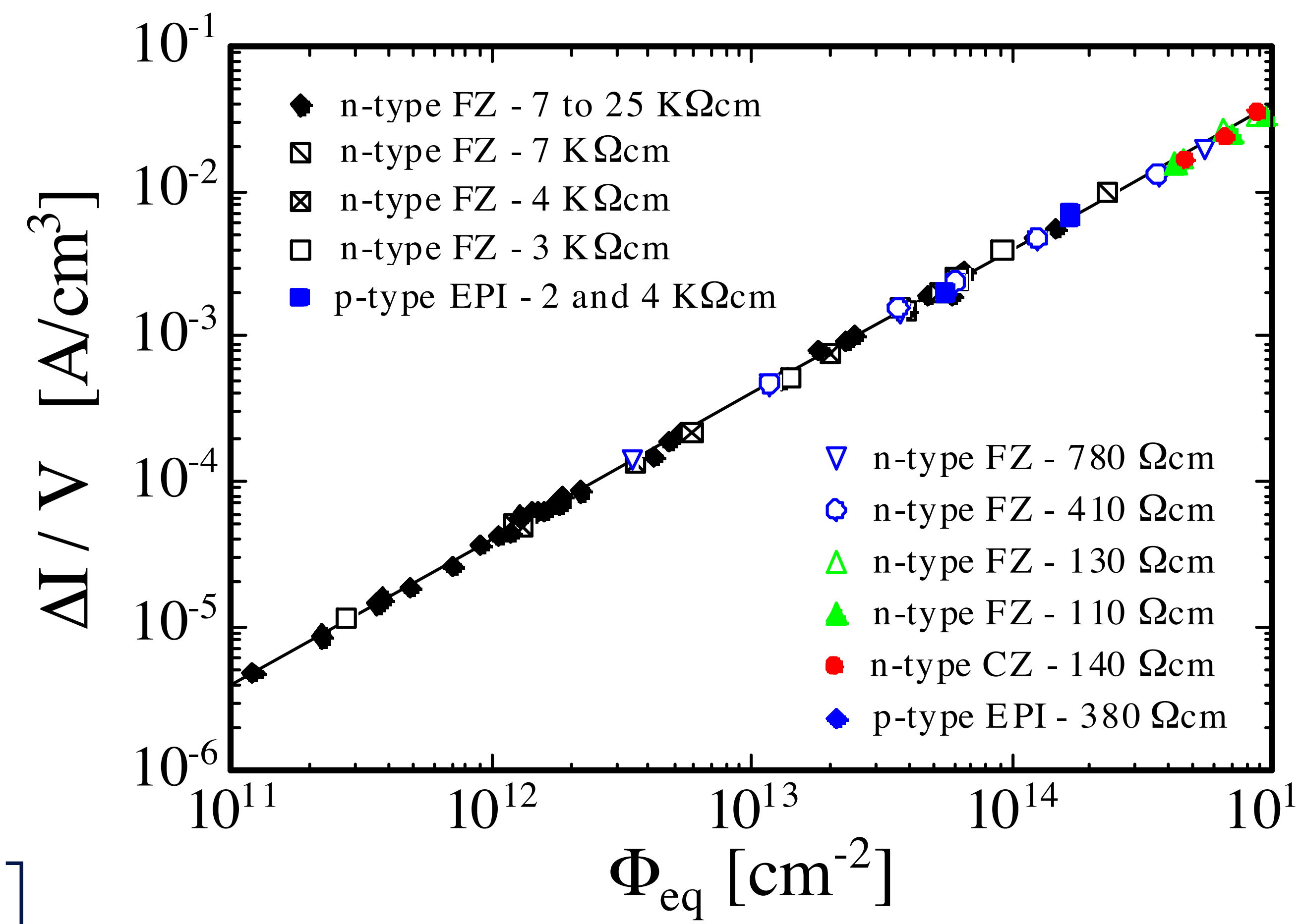
Leakage Current

- Leakage current: current flowing through sensor in reverse bias ("bulk generation current")
  - Increase of I_{leak} proportional to fluence (independent of exact silicon properties!)

$$\Delta I_{leak} = \alpha\Phi = \alpha \int \phi(E)\,dE$$

  - Rule of thump: leakage current doubles for $\Delta T \approx 7$ K

$$\frac{I_2}{I_1} = \left(\frac{T_2}{T_1}\right)^2 \exp\left[\frac{E_{gap}}{2k_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$



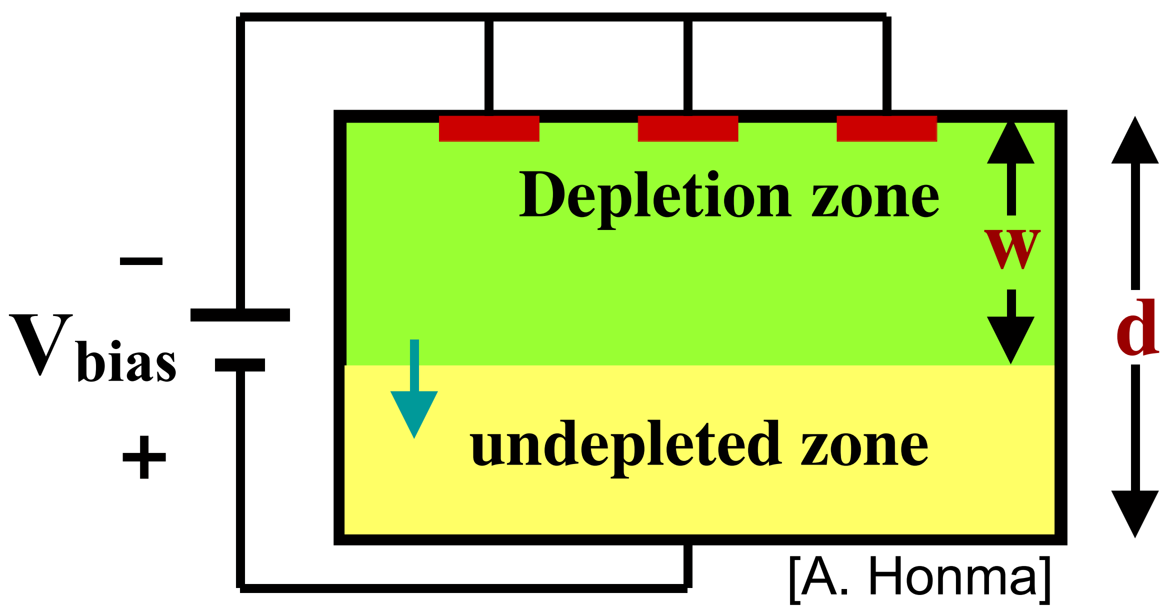
[M.Moll, PhD Thesis, U Hamburg (1999)]

$\alpha = (3.99 \pm 0.03)\times10^{-17}$ A/cm
(after 80 minutes at 60ºC)

- Problems for detector operation:
  - Additional heat load on cooling system via resistive heating
  - Vicious circle: higher temperature causes even higher leakage currents → danger of thermal runaway = uncontrolled temperature rise
  - Shot noise caused by leakage current: proportional to $\sqrt{I_{leak}}$ → deteriorates S/N

Radiation and Bias Voltage

- Depletion voltage V_{dep}: bias voltage necessary to fully deplete sensor bulk



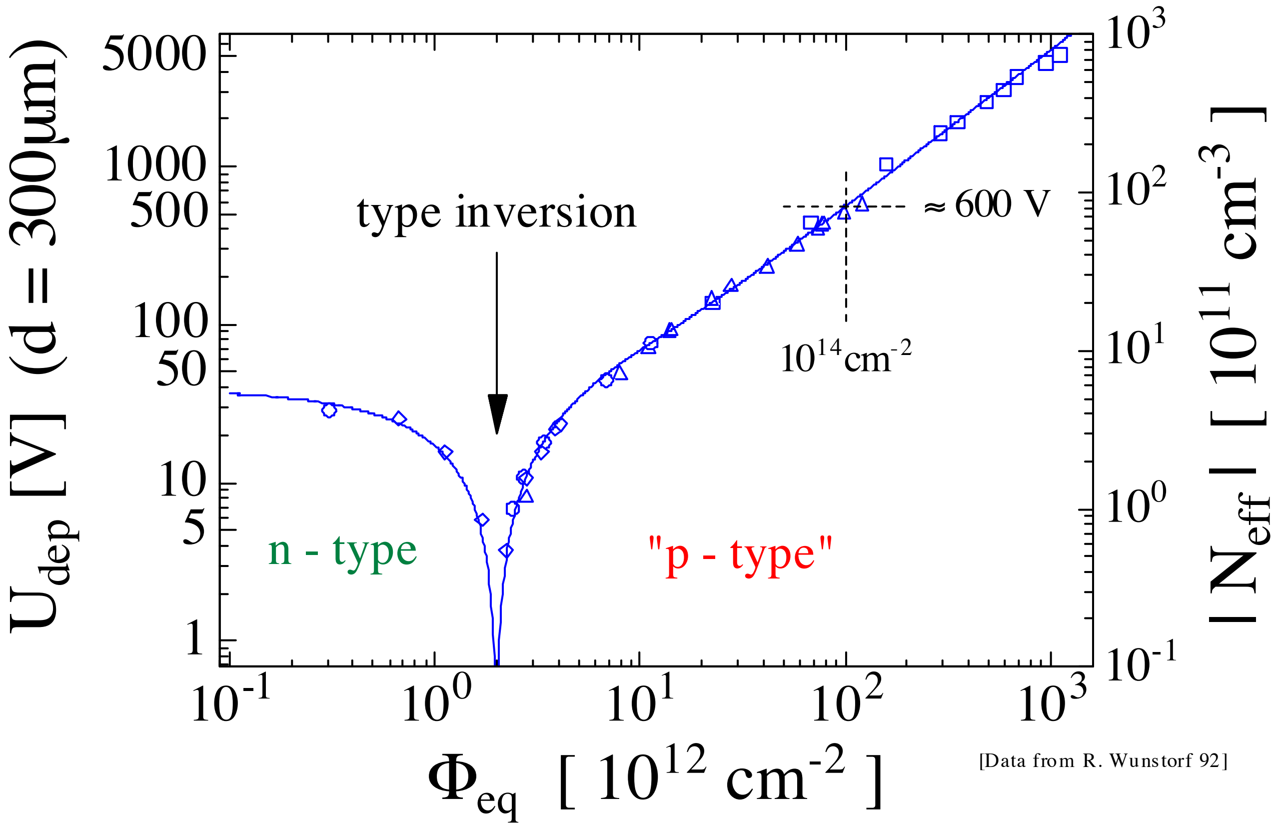
$$w(V) = \sqrt{\frac{2\varepsilon\varepsilon_0}{e\,|N_{eff}|}V_{bias}}$$

$$V_{dep} = \frac{e}{2\varepsilon\varepsilon_0}|N_{eff}|d^2$$

- Maximum signal when full sensor bulk depleted (in practice usually over-depletion, i.e. bias voltage $V_{bias} > V_{dep}$)
- Radiation damage changes effective doping concentration N_{eff}, typically from effective n-type to p-type: $V_{dep} \sim |N_{eff}|\, d^2 \rightarrow V_{bias}$ must be adjusted
- Maximum sensor bias voltage: discharges on surface (or even breakthrough) → depends on sensor design
- Technical limitations: maximum voltage from power supplies, on power lines, connectors, … → in practice 500–1000 V

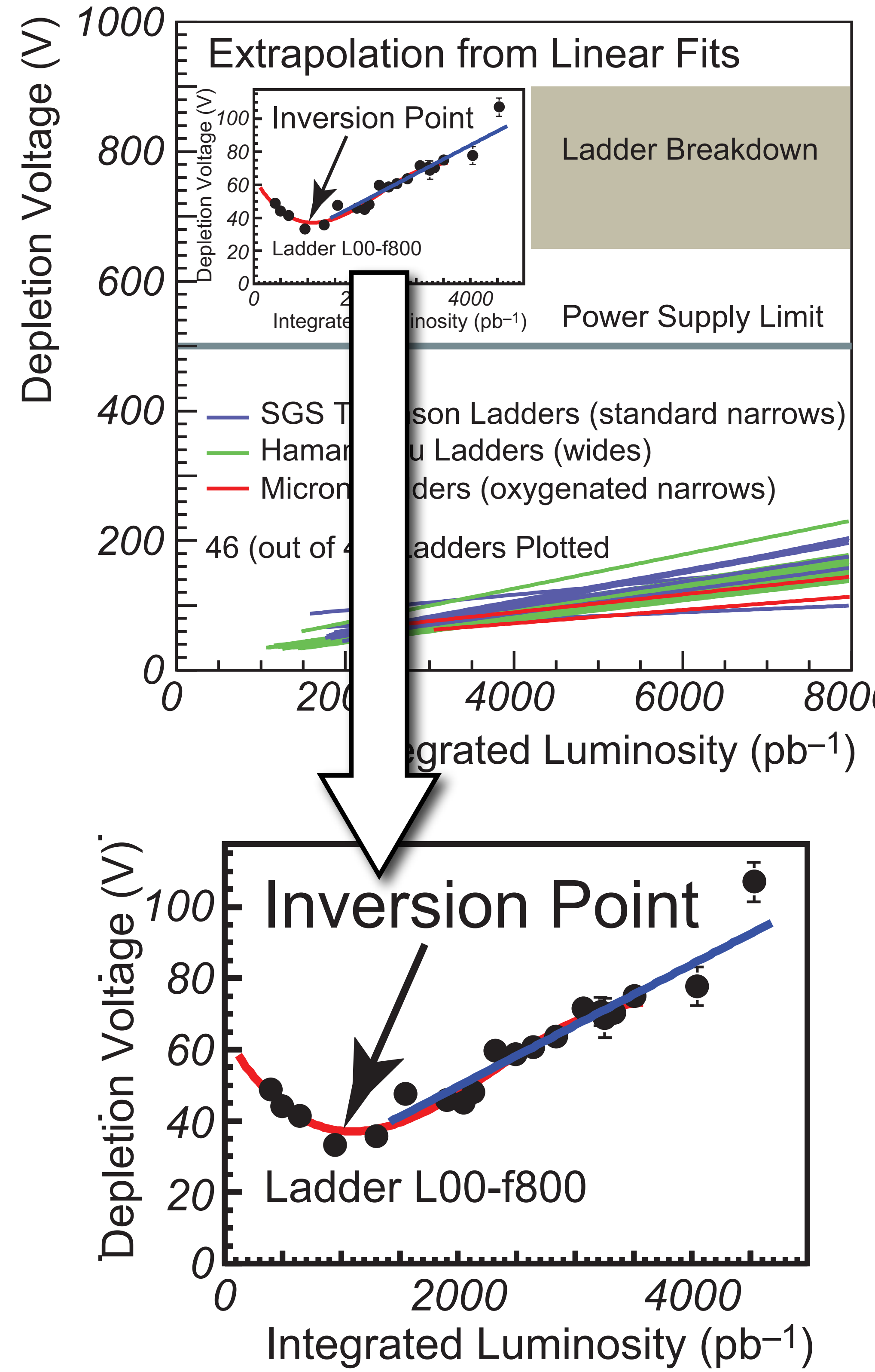
Radiation and Bias Voltage

Lab Environment



[M. Moll after R. Wunstorf,
PhD Thesis, U Hamburg (1992)]

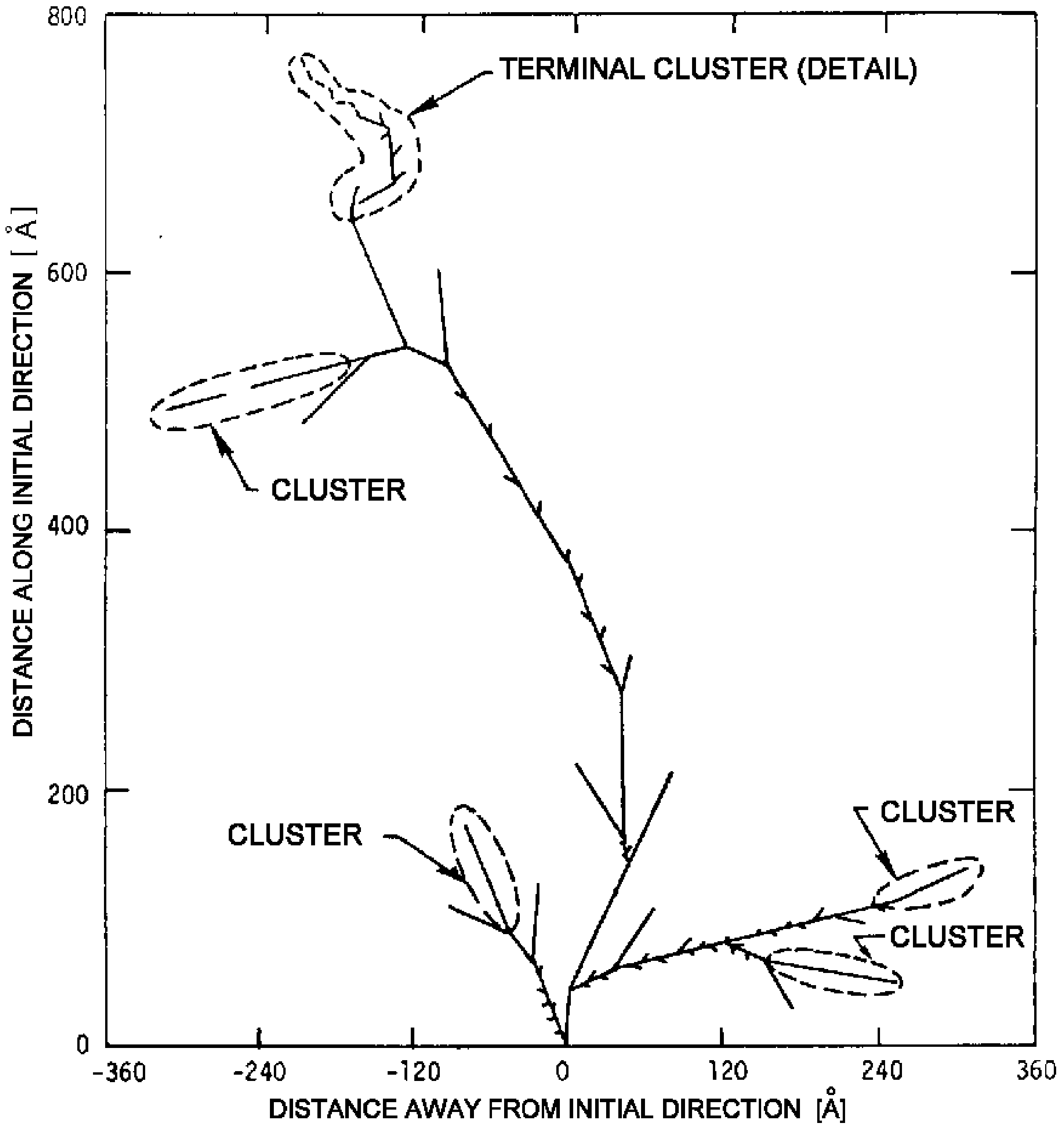
HEP Experiment (CDF)



[UH, Proc. IEEE NSS 2008]

Microscopic Picture

- Primary knock-on atom (PKA)
  - Basic process: displacement of Si atoms in lattice
  - Threshold for displacement damage: minimum recoil energy
- Classes of damage (depending on recoil energy)
  - Isolated point defects → minimum recoil energy $E_R > 15–25$ eV
  - Defect clusters = areas with large number defects → $E_R > 15$ keV
- Defects are dynamic:
  - Movement in crystal
  - Recombination with other defects
  - Annealing with high temperature



[V.A.J. van Lint et al., *Mechanisms of Radiation Effects in Electronic Materials*, Wiley 1980]

Displacement Damage Function

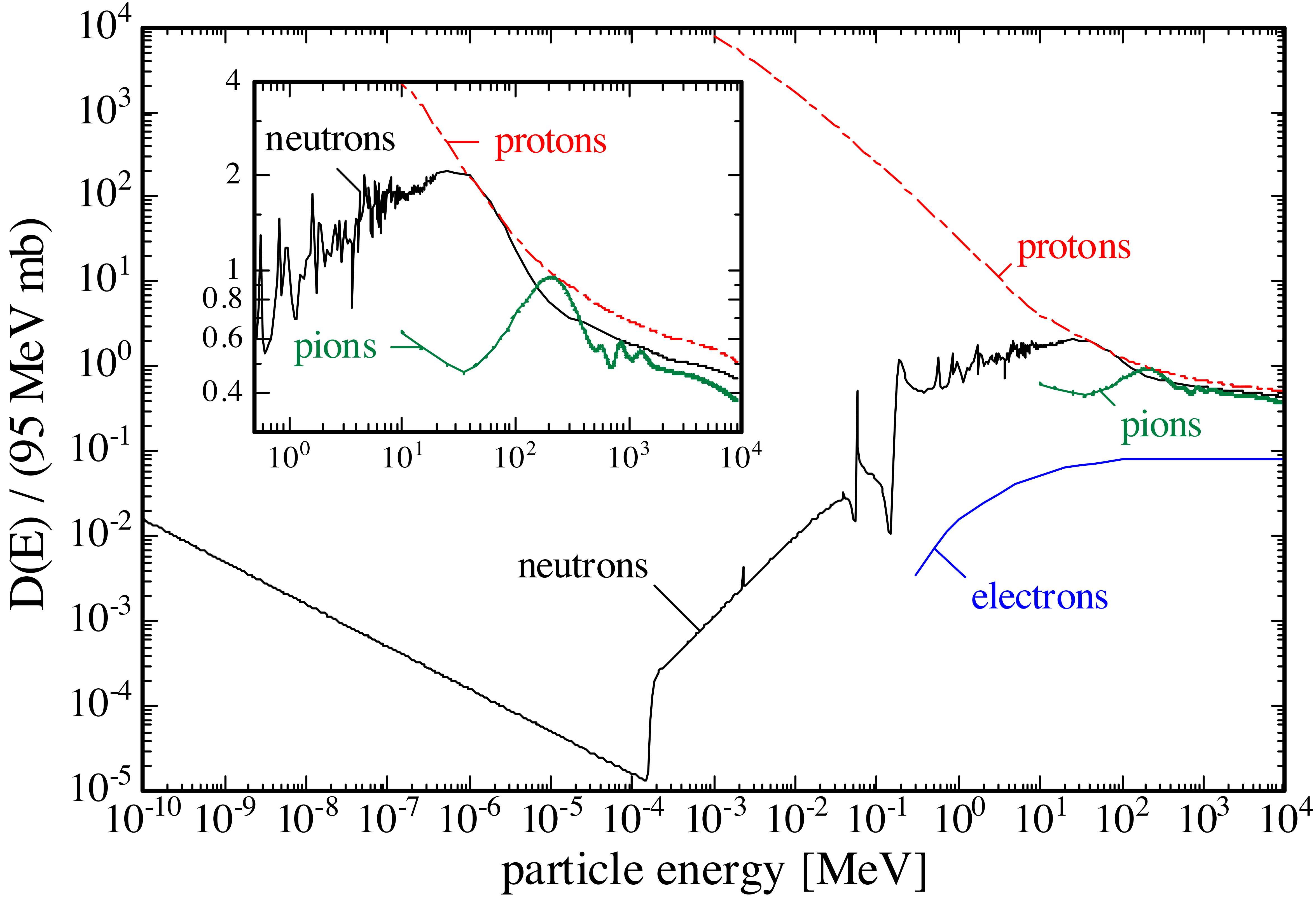
- Energy loss via ionization in silicon bulk is fully reversible (NB: damage can be significant for surface, e.g. charge accumulation at interface to oxide layer)
- Bulk damage: displacement of Si atoms by non-ionizing energy loss (NIEL)
- Energy loss usually expressed as displacement damage function $D(E)$:

$$\left.\frac{\mathrm{d}E}{\mathrm{d}x}(E)\right|_{\mathrm{NIEL}} = \frac{N_A}{A} D(E) \quad \text{with} \quad D(E) = \sum_i \sigma_i(E) \int_{E_0}^{E_R^{\max}} P(E, E_R)\, \mathrm{d}E_R$$

→ proportional to sum of cross sections σ_i for all reactions i times probability-weighted integral over all possible recoil energies E_R

- Differences between particle types, especially at low energies
  - Neutrons: elastic scattering with small cross section but large momentum transfer
  - Protons: Coulomb scattering with large cross section → likely to get many small momentum transfers → more point defects than in neutrons
  - Photons: point defects, usually no clusters

Displacement Damage Function



[M.Moll, PhD Thesis, U Hamburg (1999)]

NIEL Hypothesis

- NIEL hypothesis: all damage parameters scale with NIEL → approximation, does not hold for all particles and all energies
- Damage caused by different particles types j with given energy spectrum $\phi(E)$ can be expressed by single hardness factor κ_j

$$\kappa_j = \frac{\int \phi_j(E)\, D(E)\, \mathrm{d}E}{D_n(1\,\mathrm{MeV}) \int \phi_j(E)\mathrm{d}E}$$

- Conventional normalization to displacement damage of 1 MeV neutrons:

$$D_n(1\,\mathrm{MeV}) = 95\,\mathrm{MeV\,mb} = 2.04\,\mathrm{keV\,cm^2/g}$$

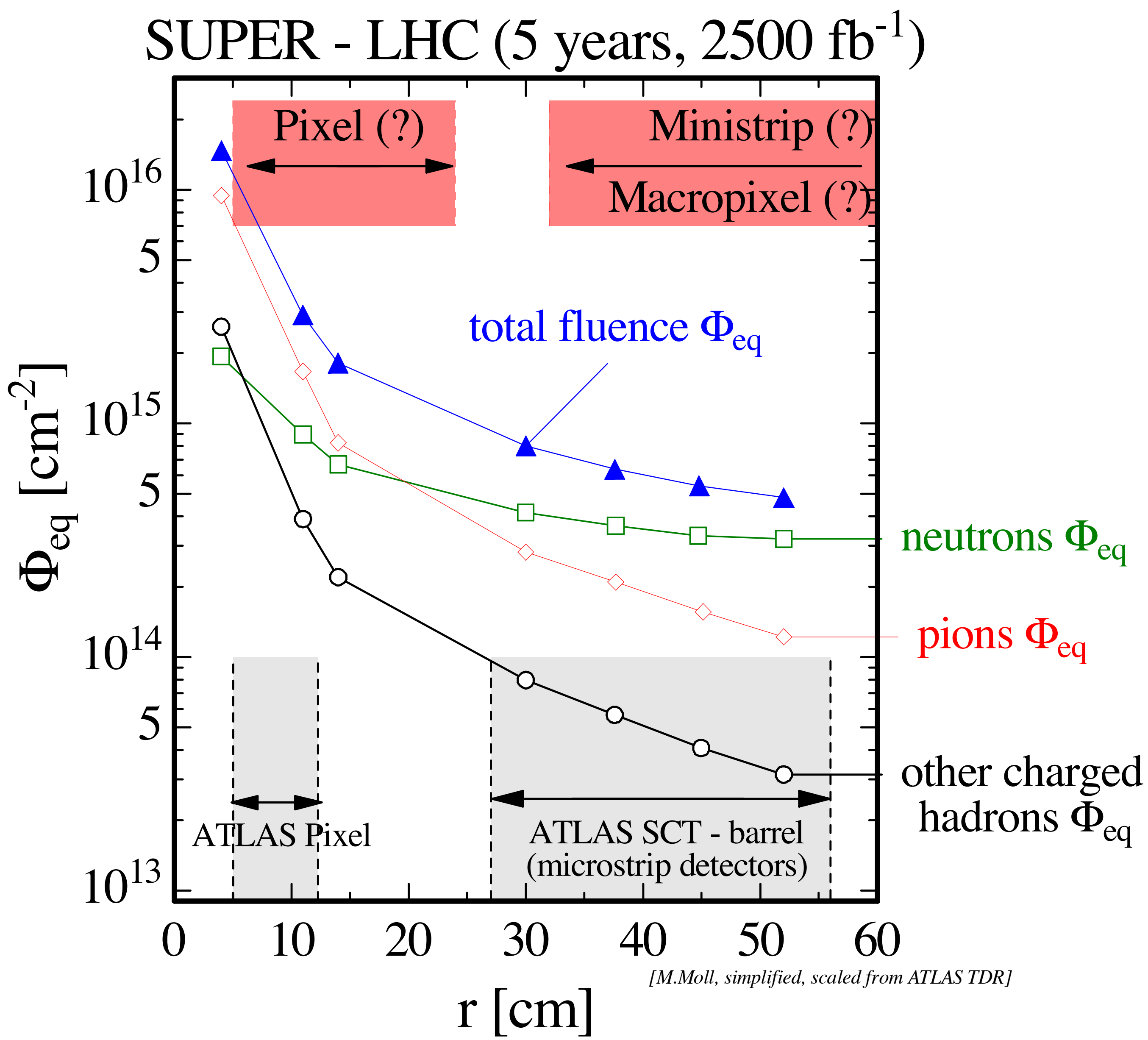
- Radiation exposure expressed by equivalent fluence Φ_{eq}:

$$\Phi_{\mathrm{eq},j} = \kappa_j\, \Phi = \kappa_j \int \phi_j(E)\, \mathrm{d}E$$

Radiation	Average Energy	Hardness Factor
Reactor Neutrons	2.1 MeV	1.06
Protons (Cyclotron)	21.1 MeV	2.72
Electrons	1.8 MeV	1.07×10^{-2}
Photons (^{60}Co)	1.25 MeV	2×10^{-6}

[R. Wunstorf, PhD Thesis, U Hamburg (1992)]

Equivalent Fluences at Hadron Colliders



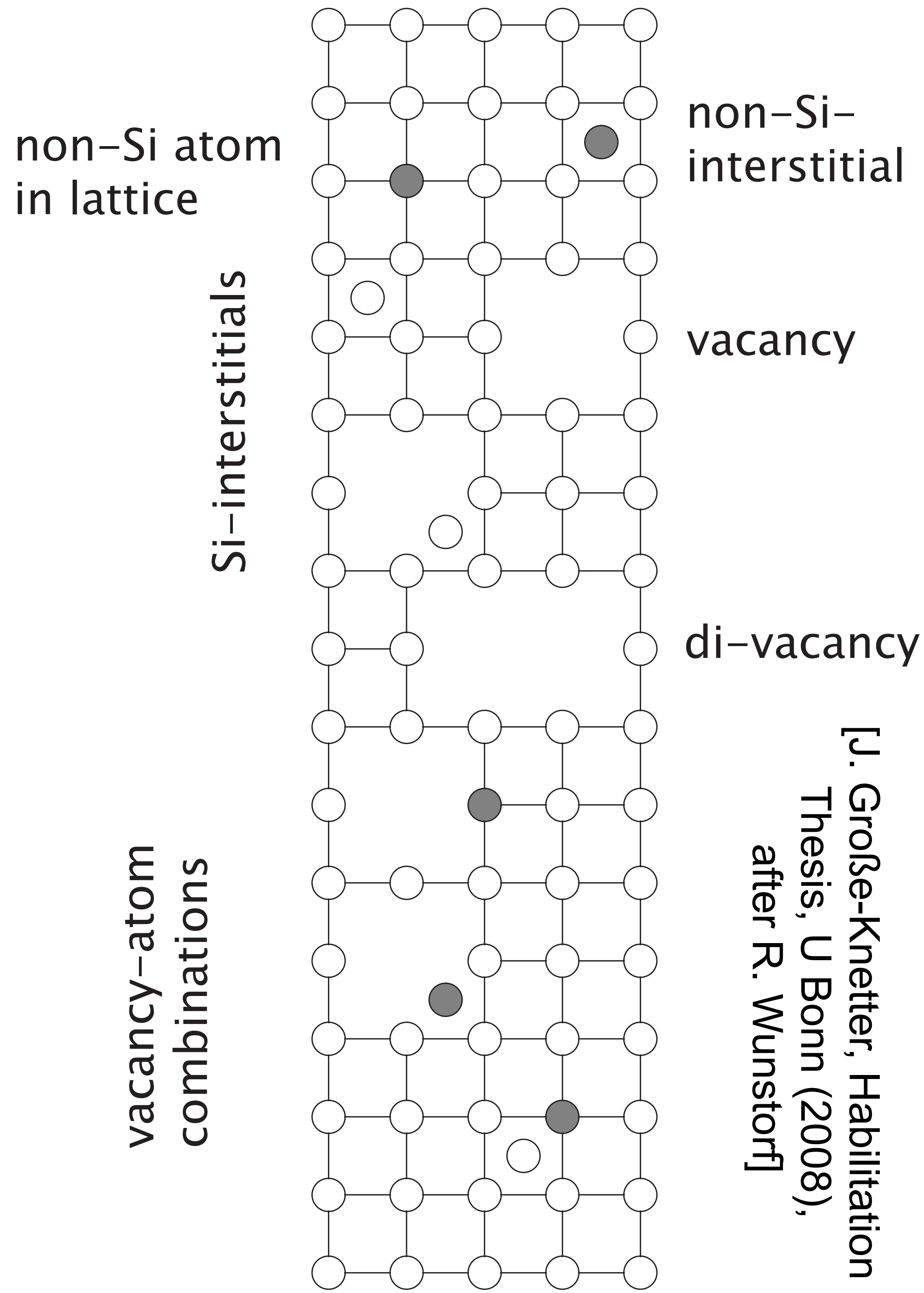
[M. Moll, ATLAS/CMS Common Electronics Workshop, CERN, March 2007]

Fluence Order of Magnitude Estimate

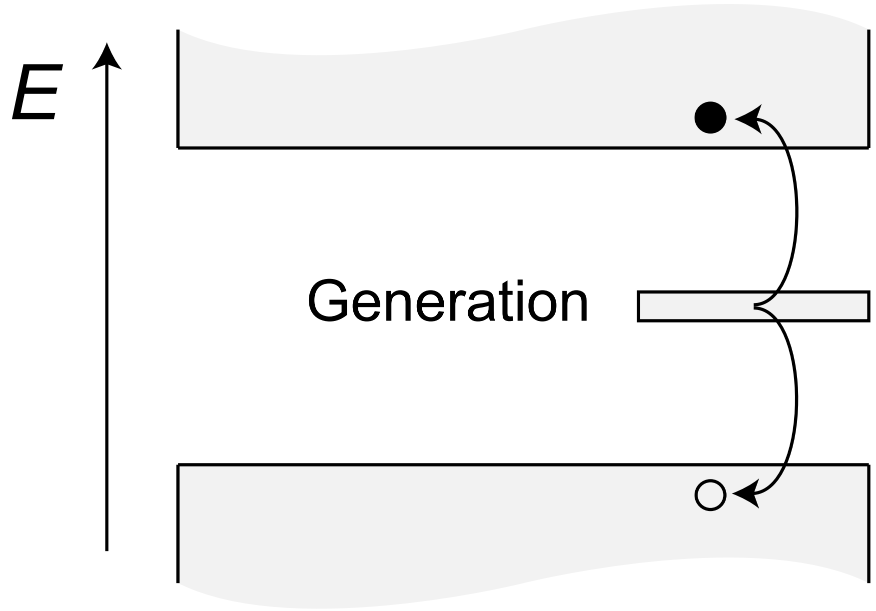
Experiment	Luminosity/ Radius	Equiv. Fluence
Tevatron (CDF)	10 fb^{-1}/ 3 cm	10^{14} cm^{-2}
LHC (ATLAS)	10 fb^{-1}/ 3 cm	10^{15} cm^{-2}
LHC-HL (ATLAS)	10 fb^{-1}/ 3 cm	10^{16} cm^{-2}

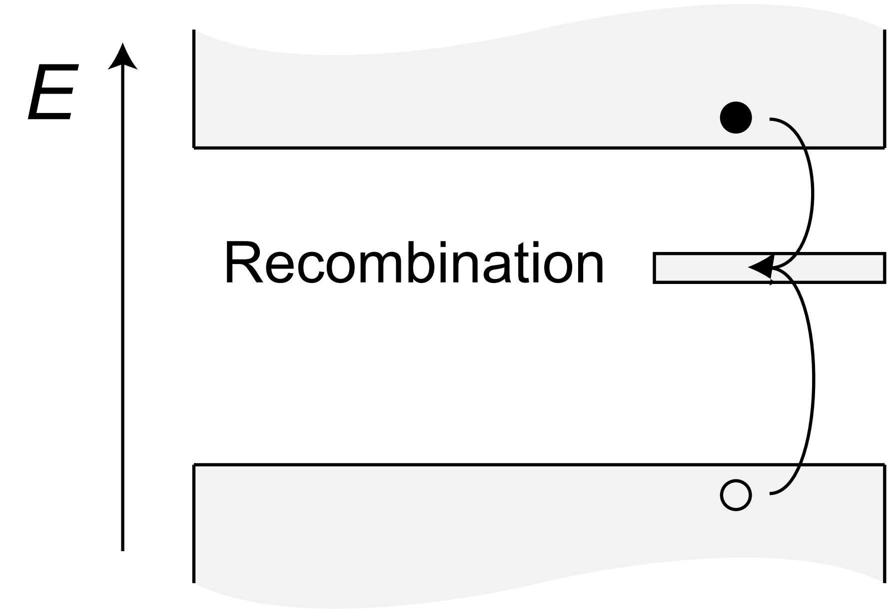
Microscopic Picture: Point Defects

- Many classes of point defects
  - Interstitials: Si (or non-Si) atoms between lattice positions ("*I*", "B_i")
  - Substitution of lattice atoms with non-Si, e.g. carbon ("C_S")
  - Vacancies in lattice ("*V*"), also di-vacancies ("V_2")
  - Combinations of the above, e.g. Frenkel defects, vacancy+oxygen ("*V–O*")
- Interstitials and vacancies: mobile at room temperature
  - Annealing via recombination
  - Stable defects via recombination with certain impurities
- Some defects: electrically active
- More details: lecture by E. Monakhov

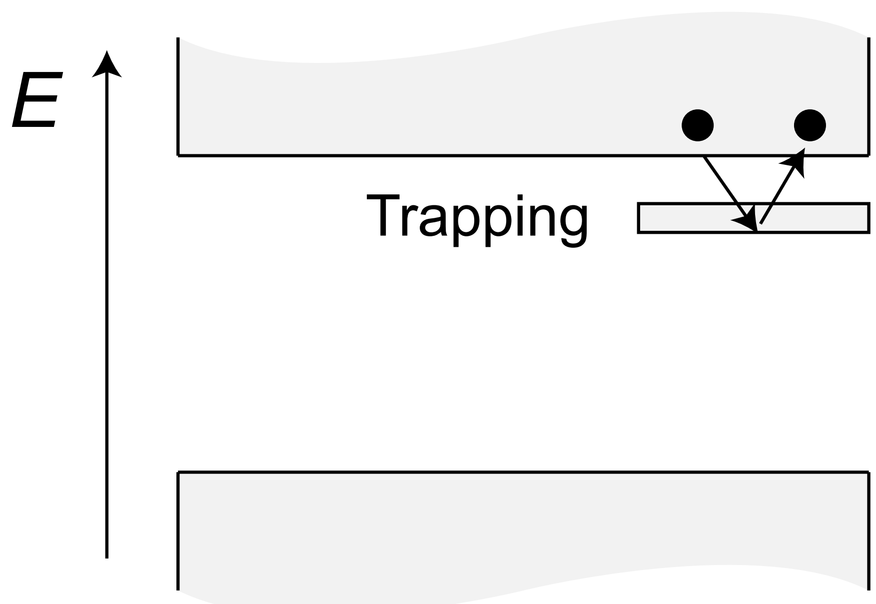


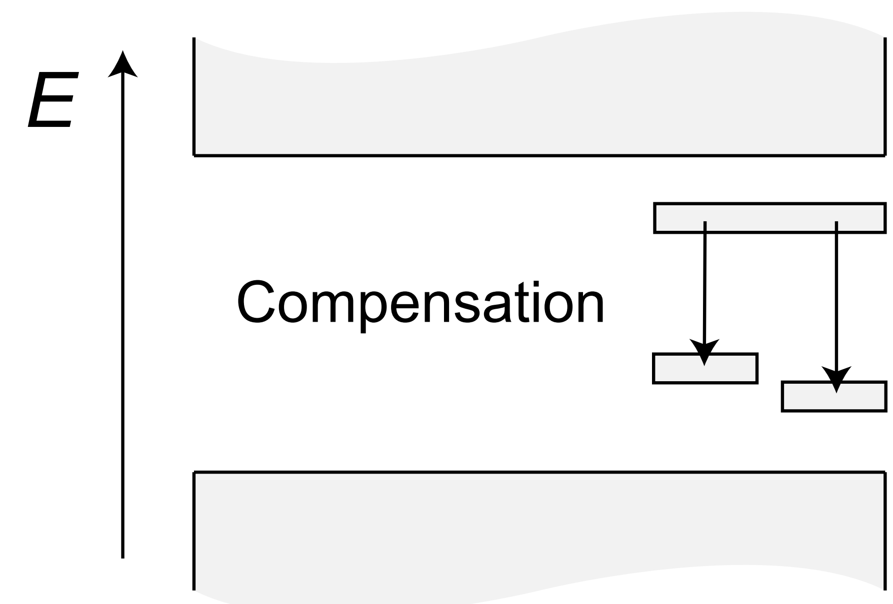
Point Defects in the Band Model





“Deep” levels (~center of band gap) → source of leakage current, e.g. *V–B*





“Shallow” levels (close to valence/conduction band) → reduced charge collection efficiency

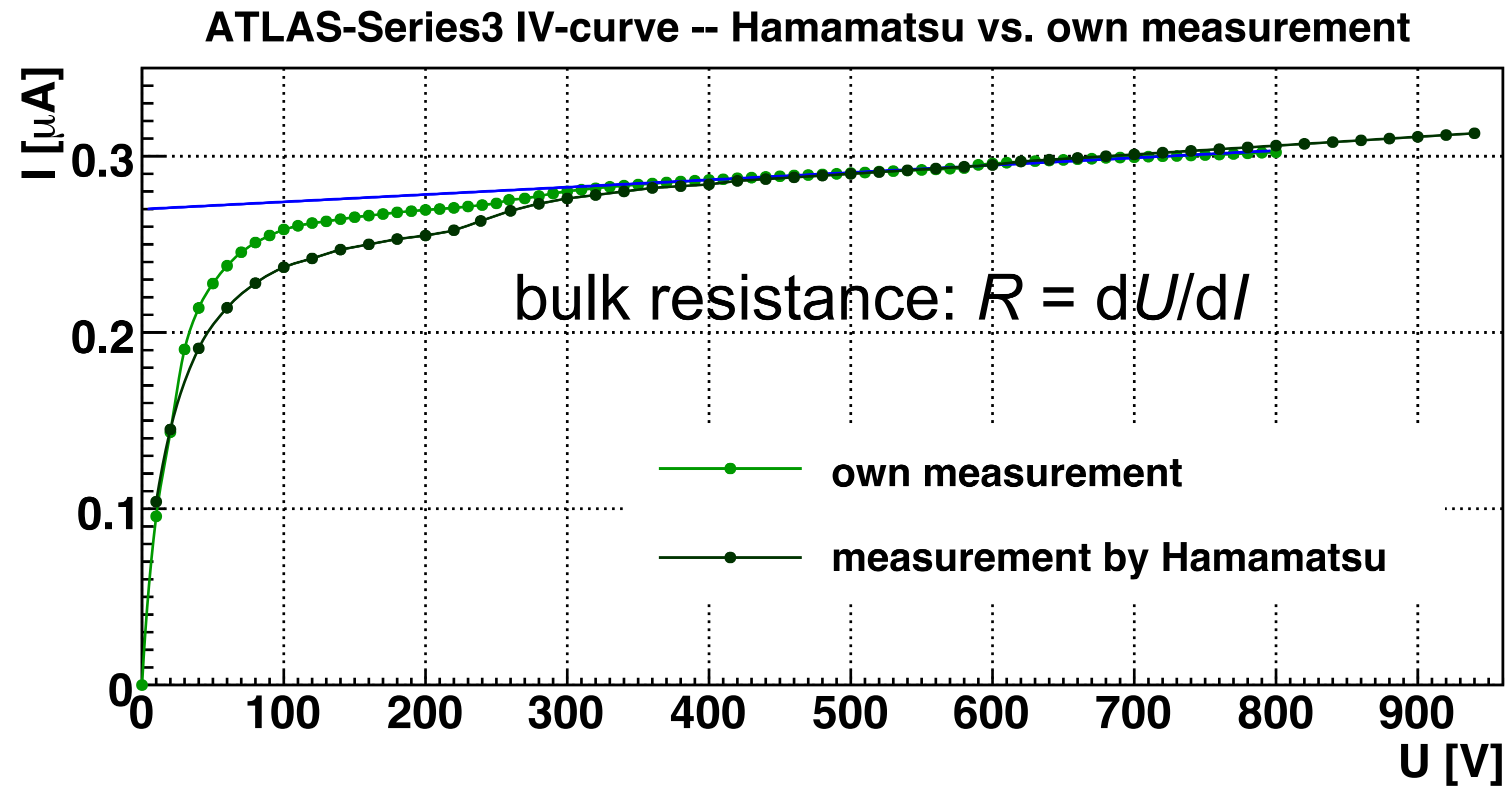
Laboratory Mesurements

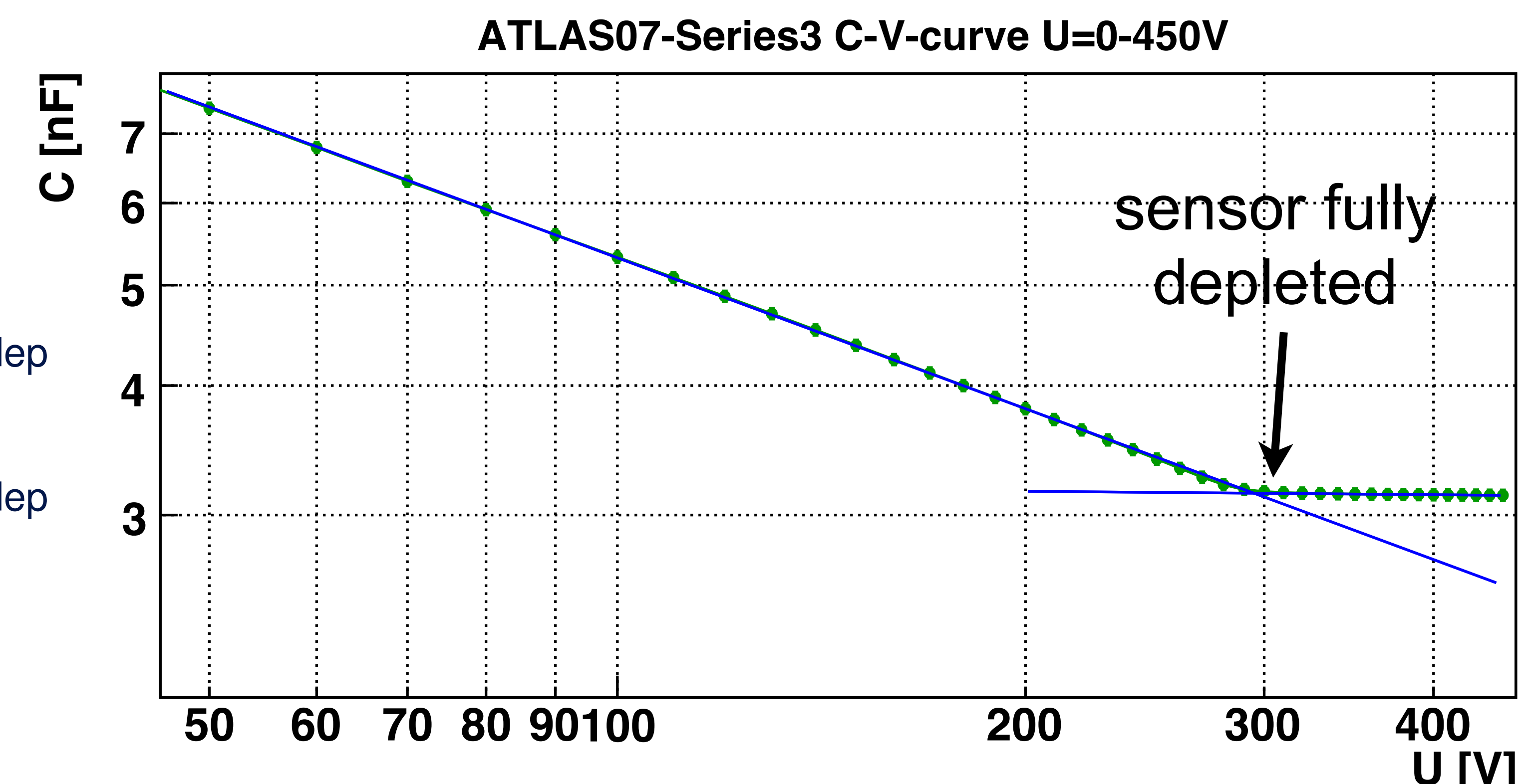
- I-V characteristic
  - Diode in reverse bias
  - Measure leakage current and bulk resistance
  - Breakthrough voltage?
- C-V characteristic
  - Idea: capacitance drops until no all charge carriers removed

$$C(V) = A\sqrt{\frac{\varepsilon\varepsilon_0 e|N_{\mathrm{eff}}|}{2V}} \quad \text{for } V \leq V_{\mathrm{dep}}$$

$$C(V) = \frac{\varepsilon\varepsilon_0 A}{d} \quad \text{for } V > V_{\mathrm{dep}}$$

  - Measure depletion voltage

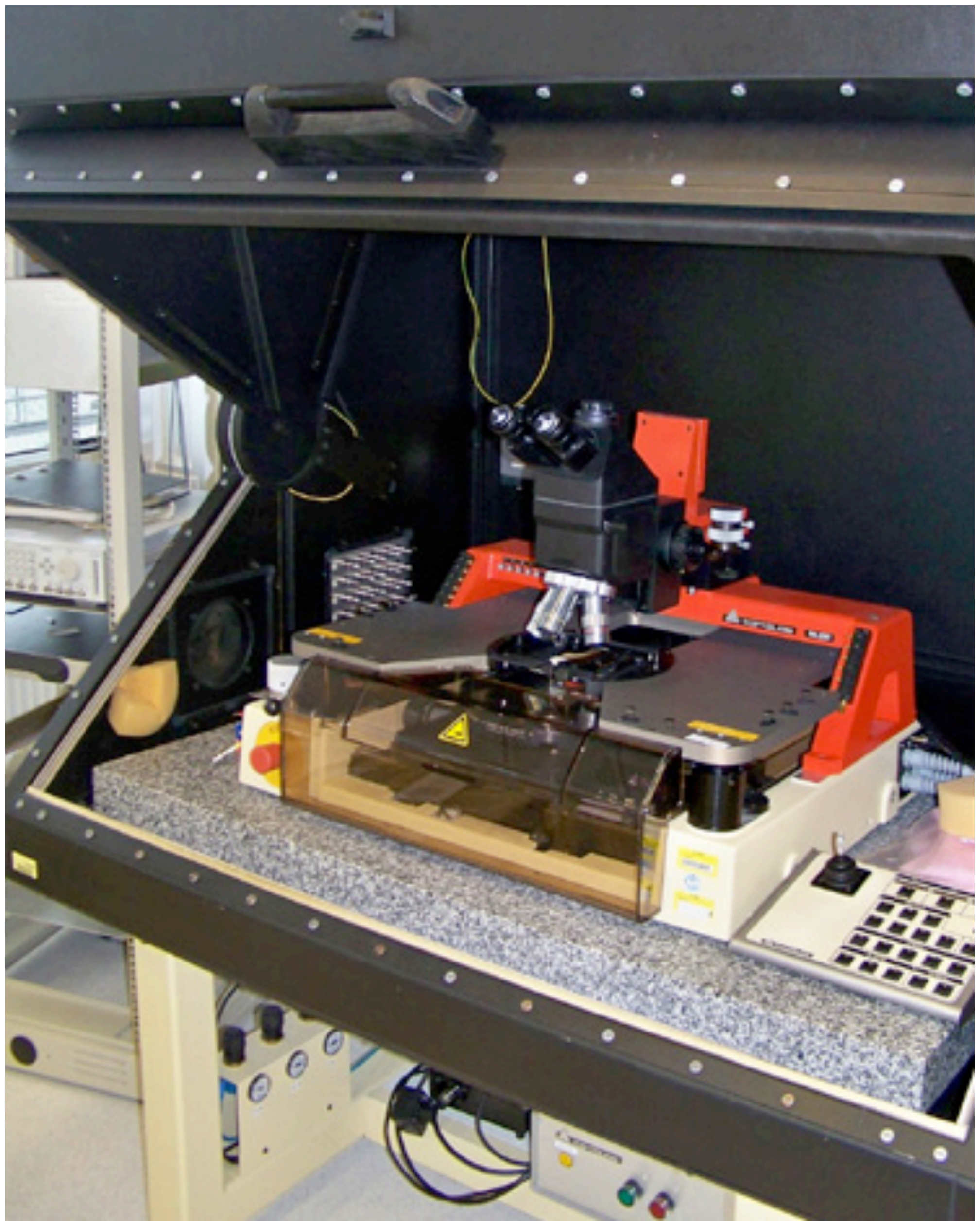




[M. Boronat, C. Friedrich, H. Zhu]

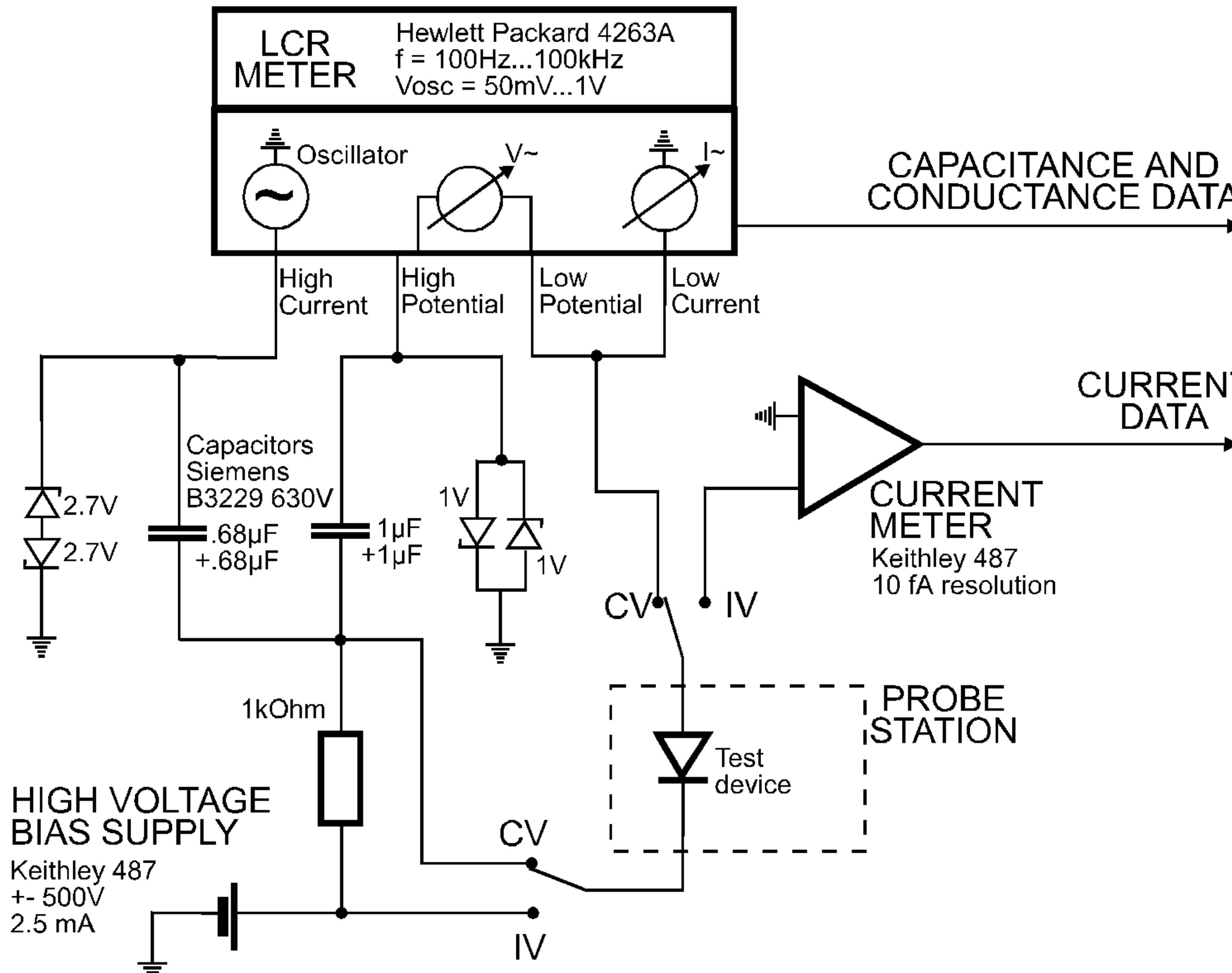
Typical Laboratory Setup

Probe Station



precise (automatic) positioning of probe needles on bond pads of sensors

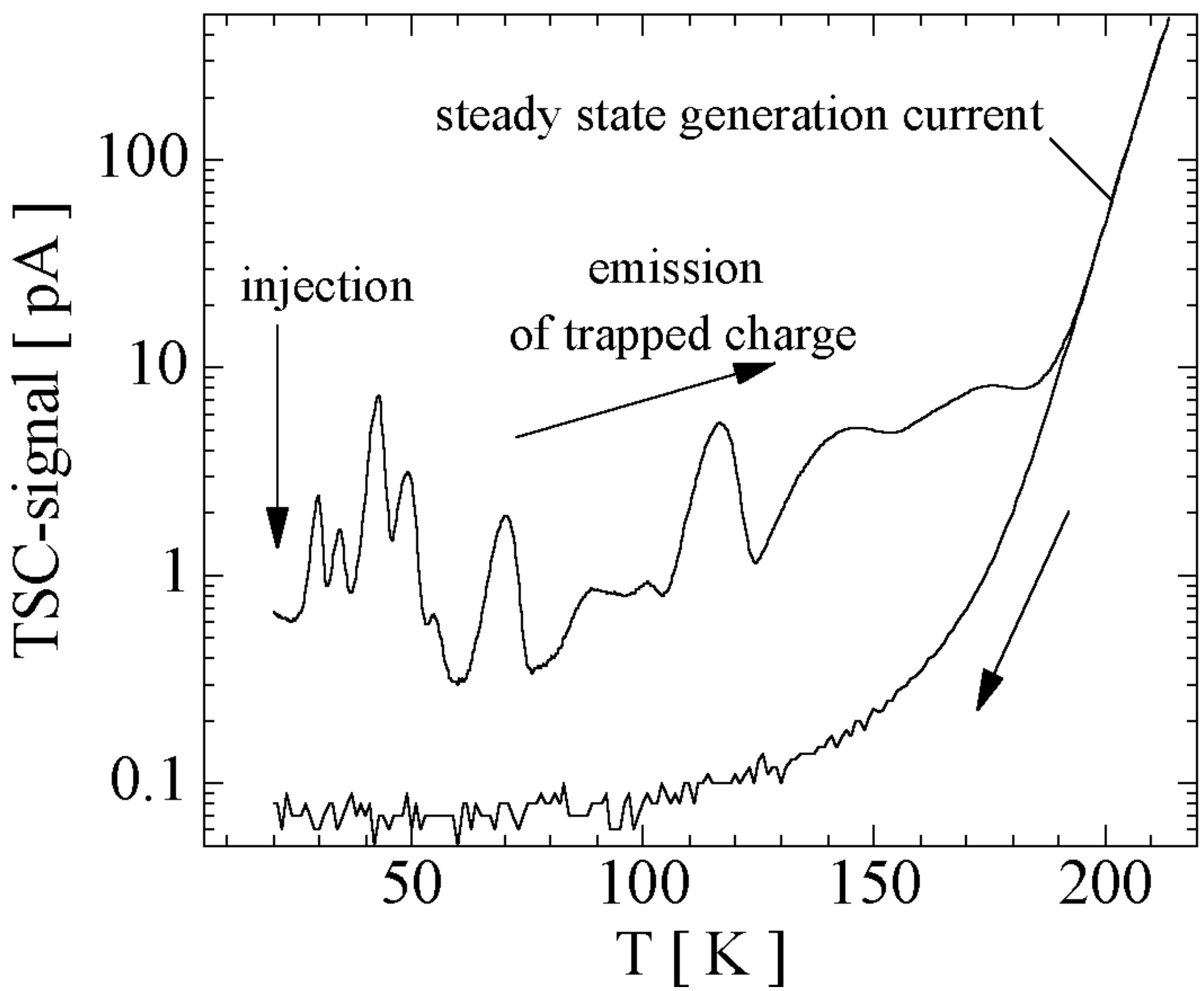
Electronics Setup



[H. Feick, PhD Thesis, U Hamburg (1997)]

Measuring Microscopic Defects

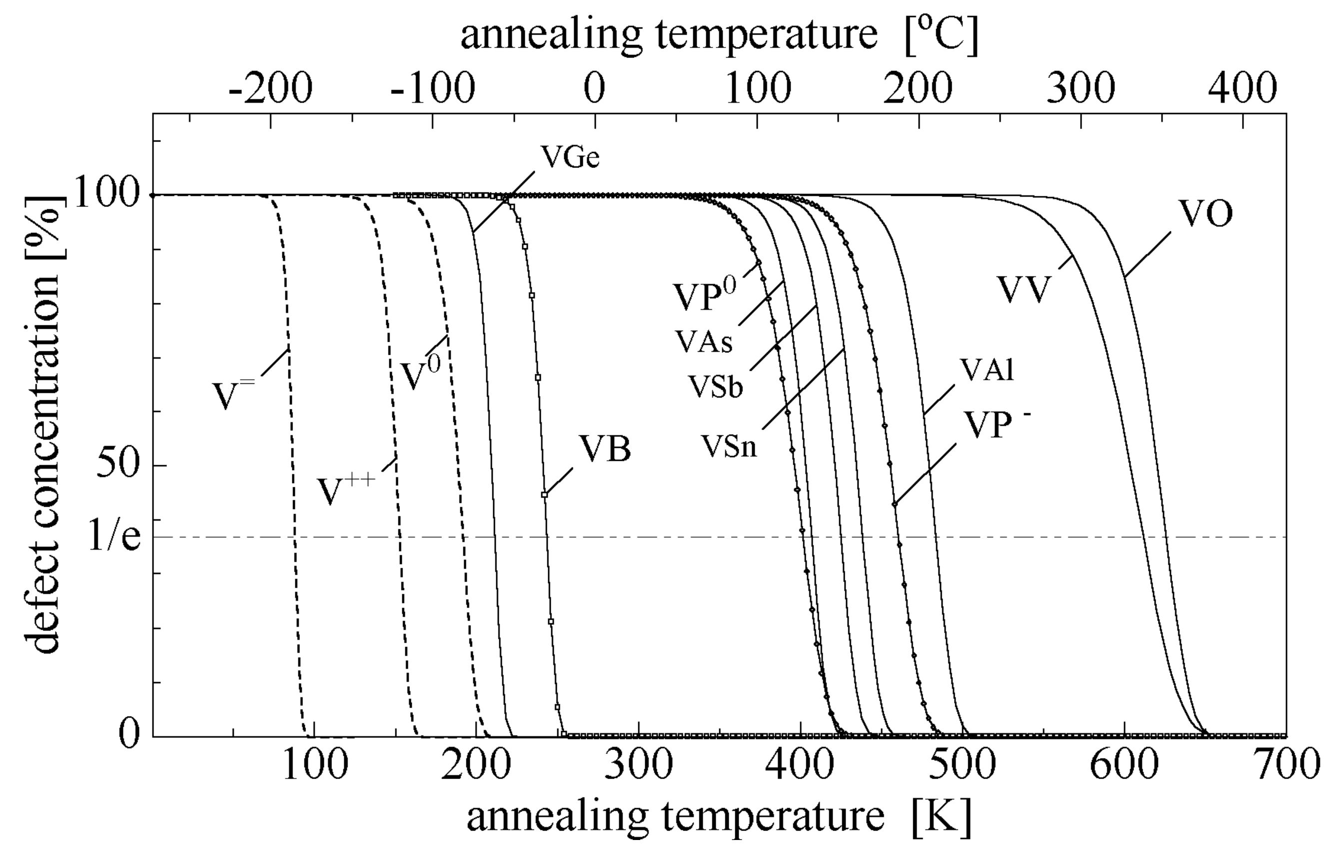
- Deep Level Transient Spectroscopy (DLTS)
  - Introduce free charge carriers into depleted sensors, e.g. by pulsing bias voltage (0 V or forward bias)
  - Analyze system answer transient, e.g. capacitance over time → defect concentration, activation energy, electron/hole capture cross section …
  - More in lecture by Edouard Monakhov on Wednesday
- Thermally Stimulated Current (TSC) spectroscopy
  1. Cool down sensor under reverse bias, monitor bulk generation current
  2. Inject free charge carriers at low temperature (e.g. 20 K): forward bias or illumination with laser that fits band gap
  3. Heat sensor → trapped charges released at specific temperatures: characteristic current peaks

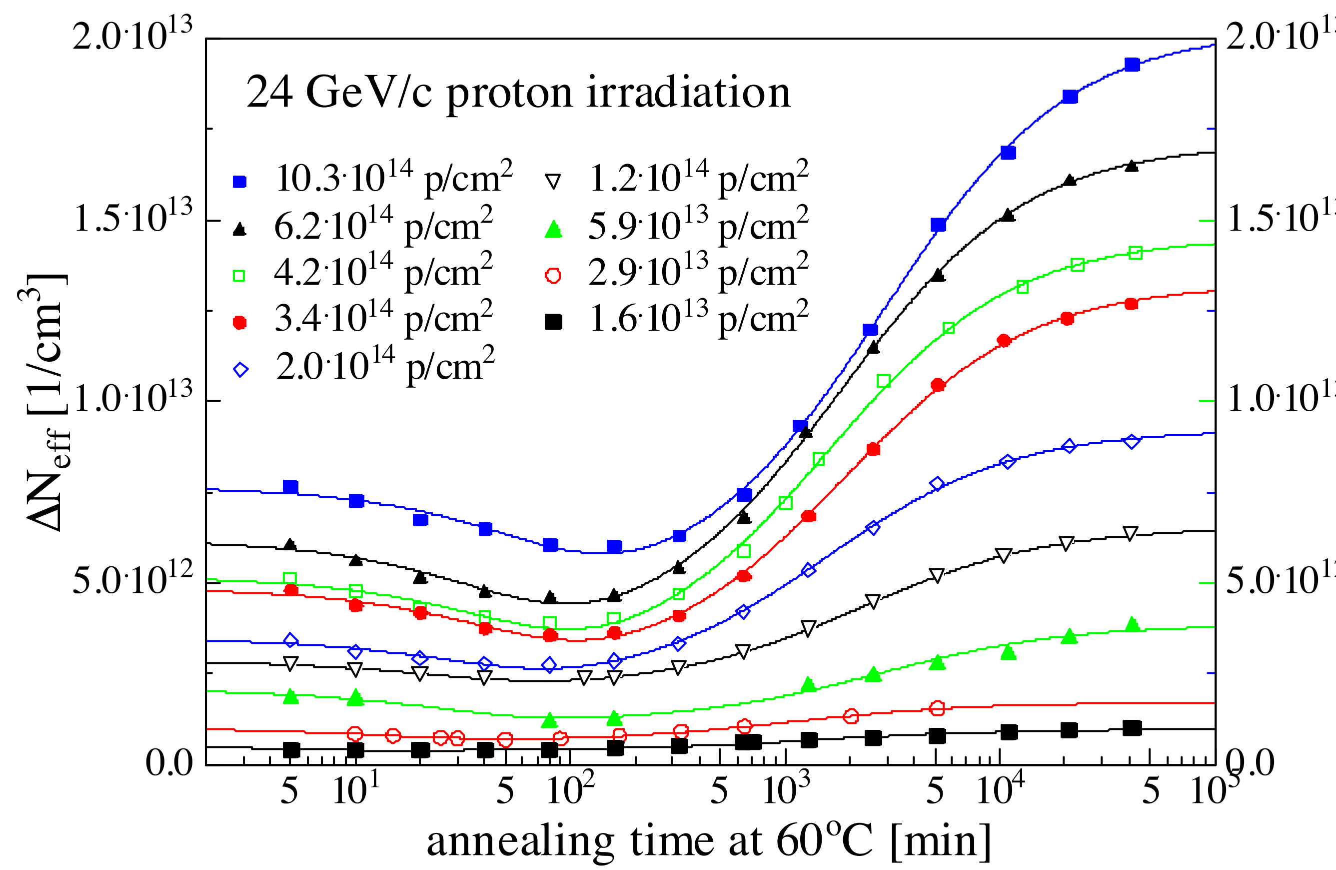


[M. Moll, PhD Thesis, U Hamburg (1999)]

Annealing of Sensor Defects

- Defect annealing
  - Above a certain temperature: migration of defects → defects can be gettered e.g. at surface or recombine with counterpart (e.g. $Si_I + V \rightarrow Si_S$) or form new defects
  - Lattice vibrational energy larger than binding energy: dissociation of complex defects
  - Annealing studies: information on defects in addition to activation energy and capture cross section
- Classification
  - Short term beneficial annealing
  - Stable damage
  - Long term reverse annealing





[M. Moll]

Summary – defects with strong impact on the device properties at operating temperature

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3\cdot10^{-14}$ cm^2
  - $\sigma p^{I} = 2.3\cdot10^{-14}$ cm^2

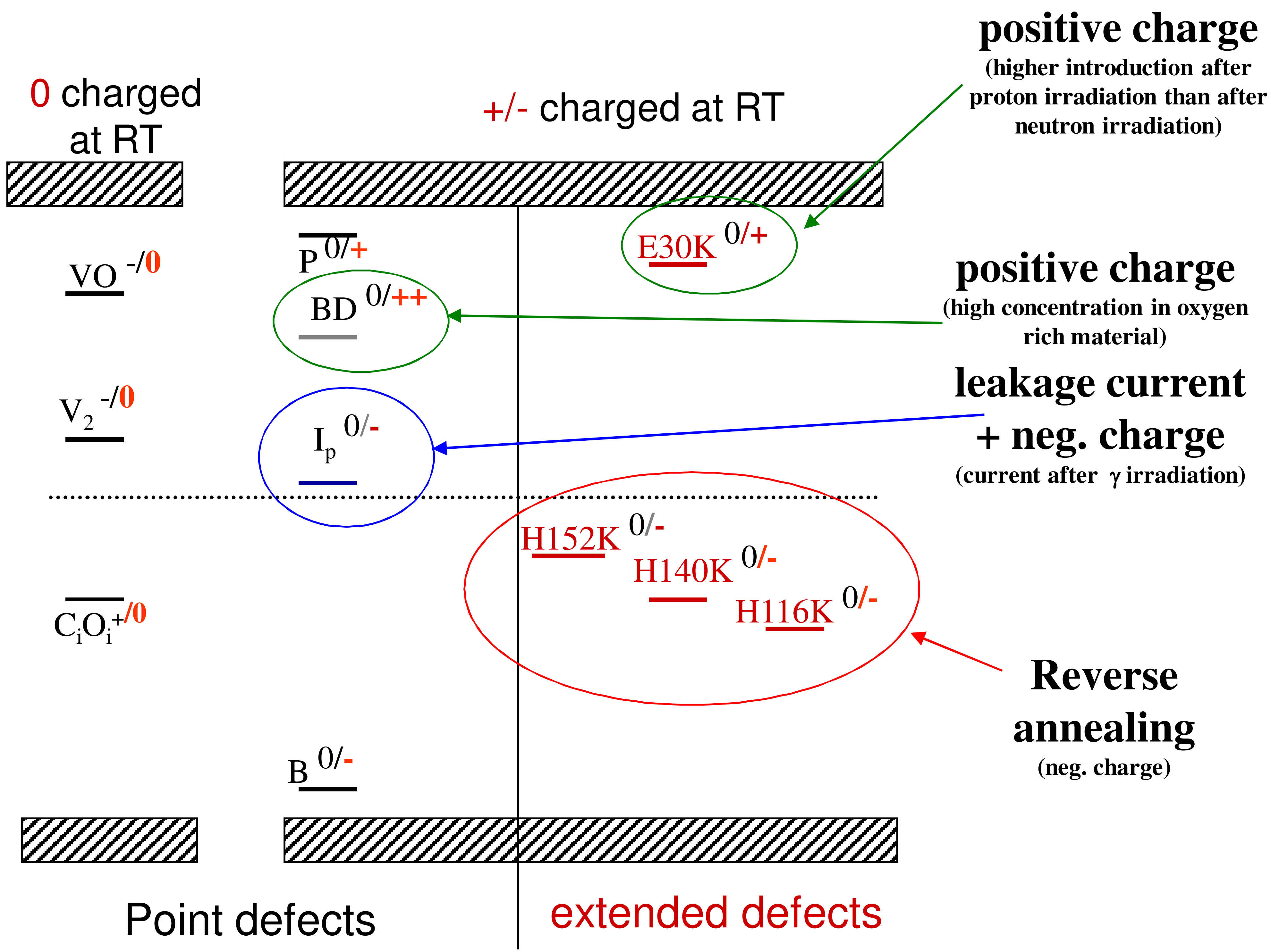
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4\cdot10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5\cdot10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3\cdot10^{-14}$ cm^2



Hamburg Model

- Phenomenological "Hamburg model" to describe annealing
- Change in effective charge carrier concentration (or equivalently depletion voltage):

$$\Delta N_{\text{eff}} = N_A + N_C + N_Y$$

- Beneficial annealing:

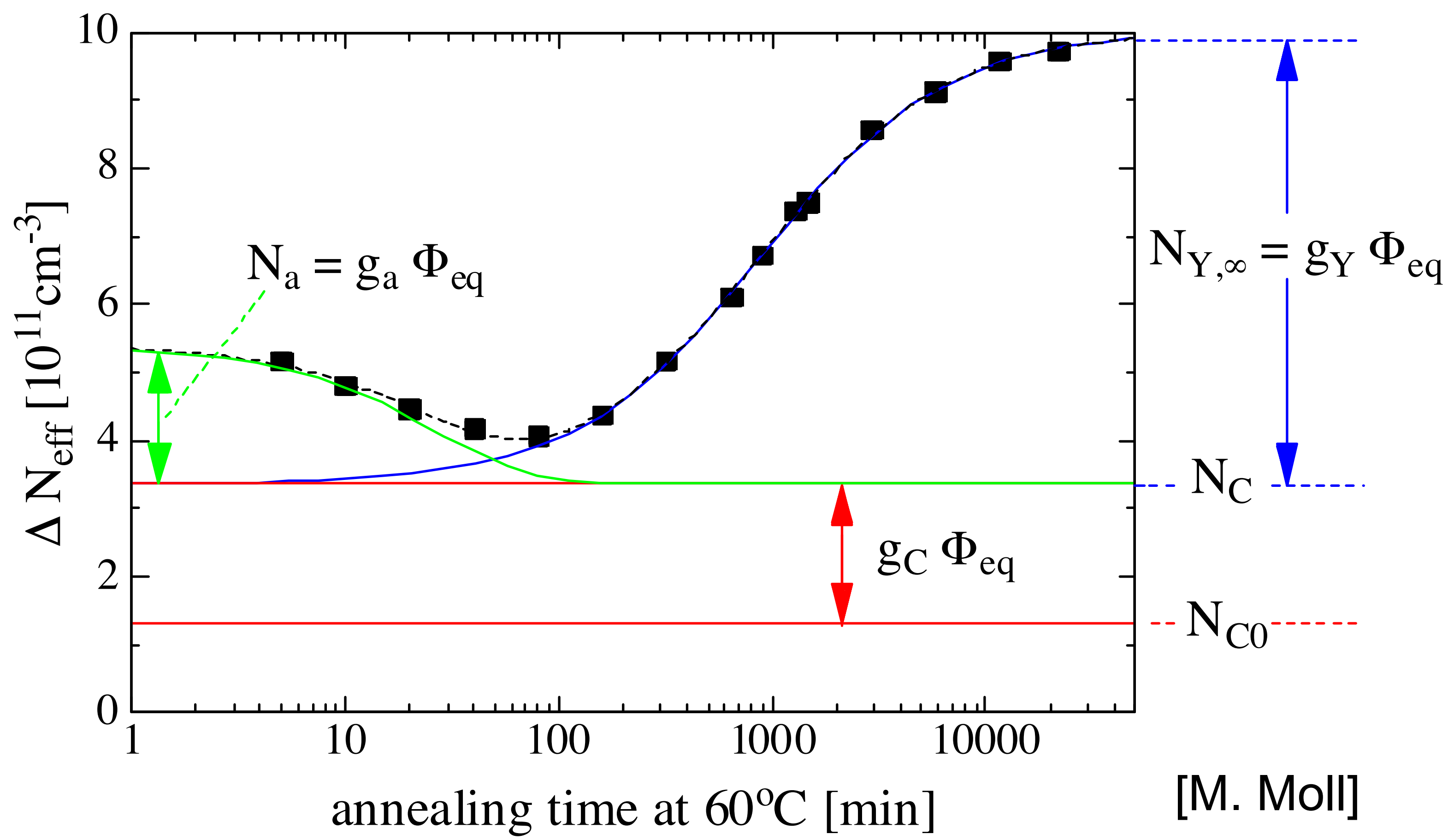
$$N_A = \Phi_{\text{eq}} \sum_i g_{A,i} \exp[-c_{A,i}(T)\, t]$$

- Stable damage:

$$N_C = N_{C,0}\left(1 - \exp[-c_C \Phi_{\text{eq}}]\right) + g_C \Phi_{\text{eq}}$$

- Reverse annealing:

$$N_Y = g_Y \Phi_{\text{eq}} \left(1 - \frac{1}{1 + g_Y \Phi_{\text{eq}}\, c_Y(T)\, t}\right)$$

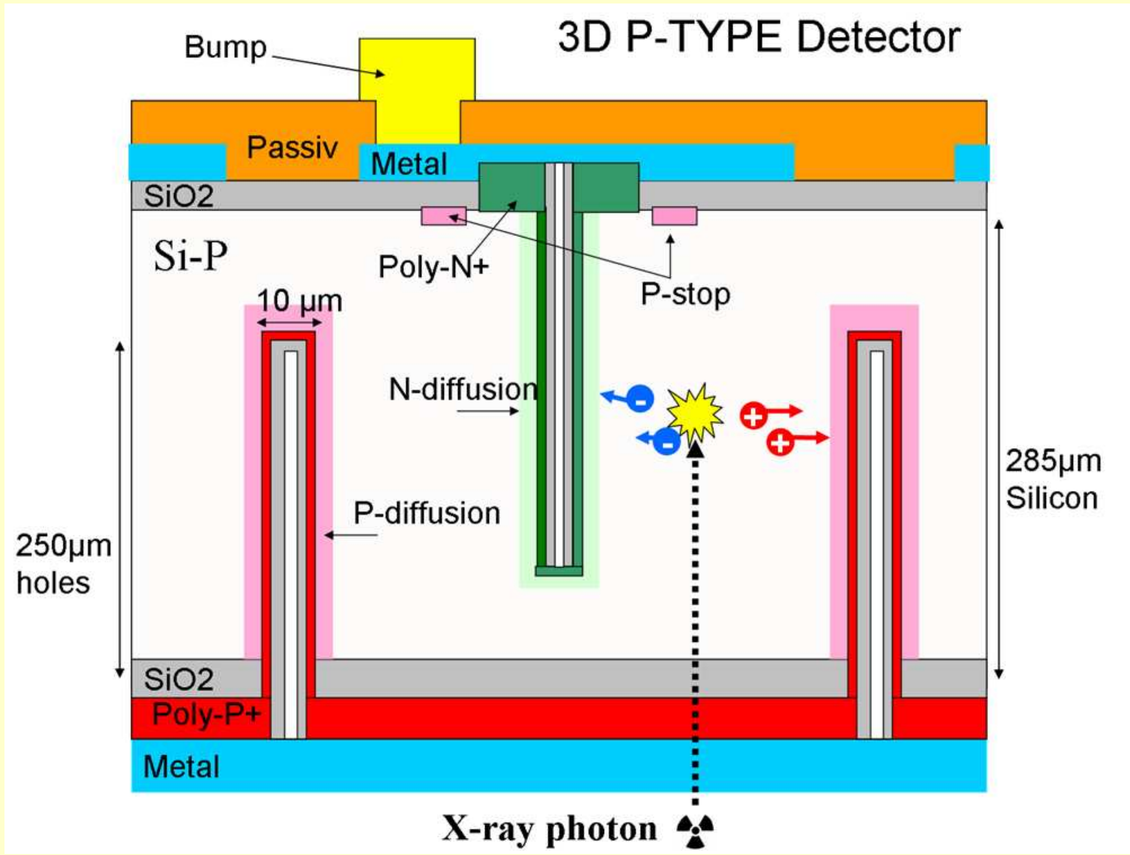


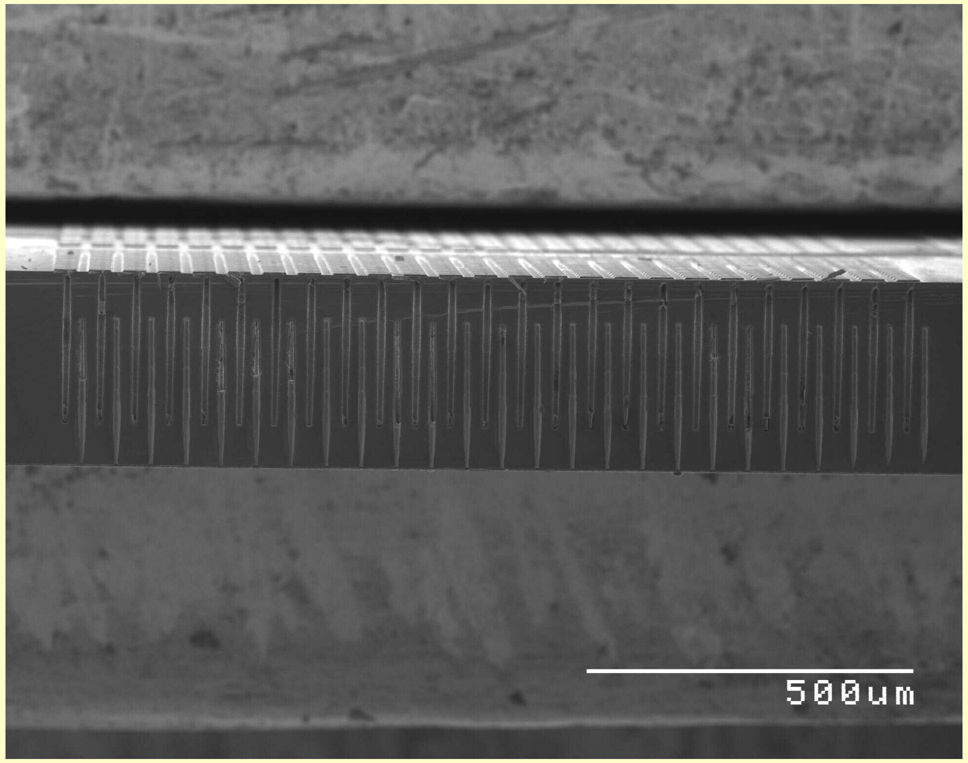
[M. Moll]

Used extensively to predict silicon detector lifetimes, e.g. CDF, CMS

A Look into the Future

- Current CERN planning: run LHC until about 2030 (“LHC-HL”) → integrated luminosity: 3000 fb^{-1}
- R&D on detectors for very high equivalent fluences > 10^{16} cm^{-2}
  - 3D silicon sensors
  - Strip sensors with p-bulk
- 3D silicon sensors at a glance:
  - Instead of strips: narrow (10 µm) columns along sensor thickness
  - Advantage: decouple charge collection and sensor thickness
  - Shorter charge collection distance: lower depletion voltage, faster signal, less trapping → radiation hard

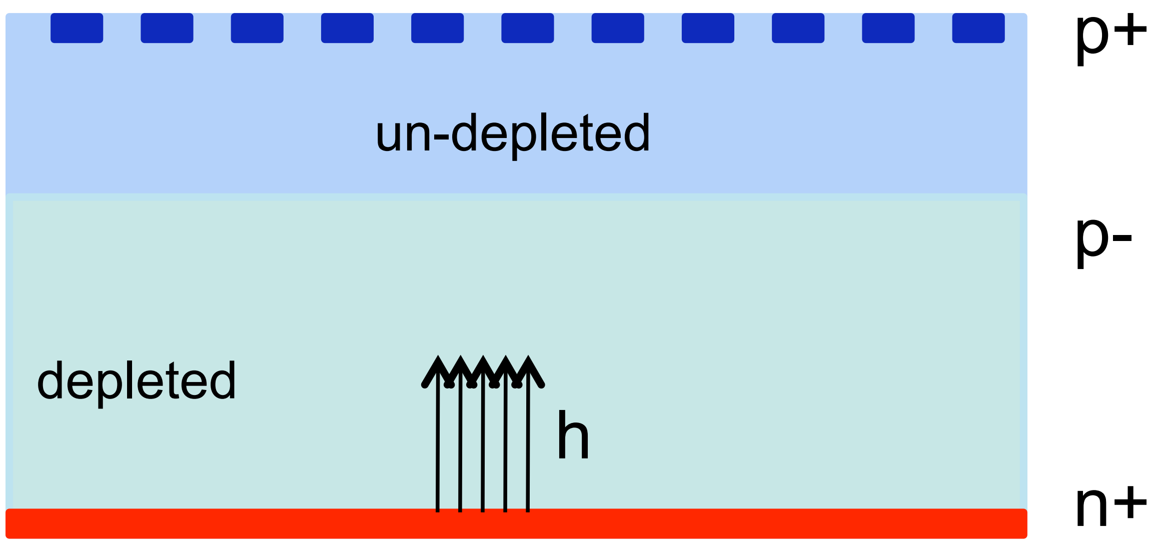




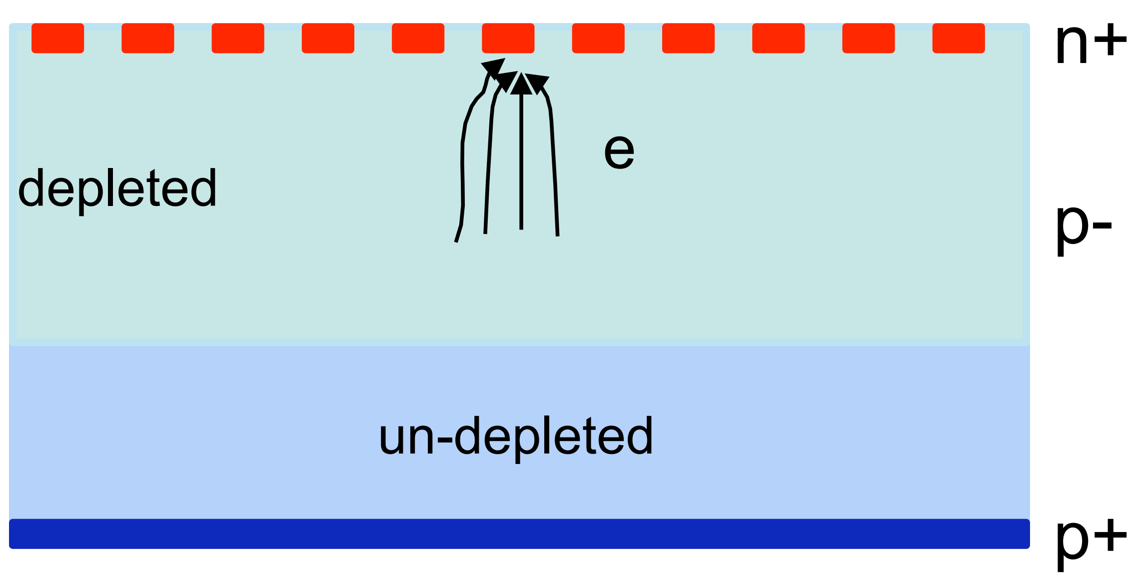
[C. Fleta, RD50 Workshop, Barcelona 2010]

Sensors with p-Type Bulk

p-in-n Sensor after Type Inversion



n-in-p Sensor
(or n-in-n after type inversion)

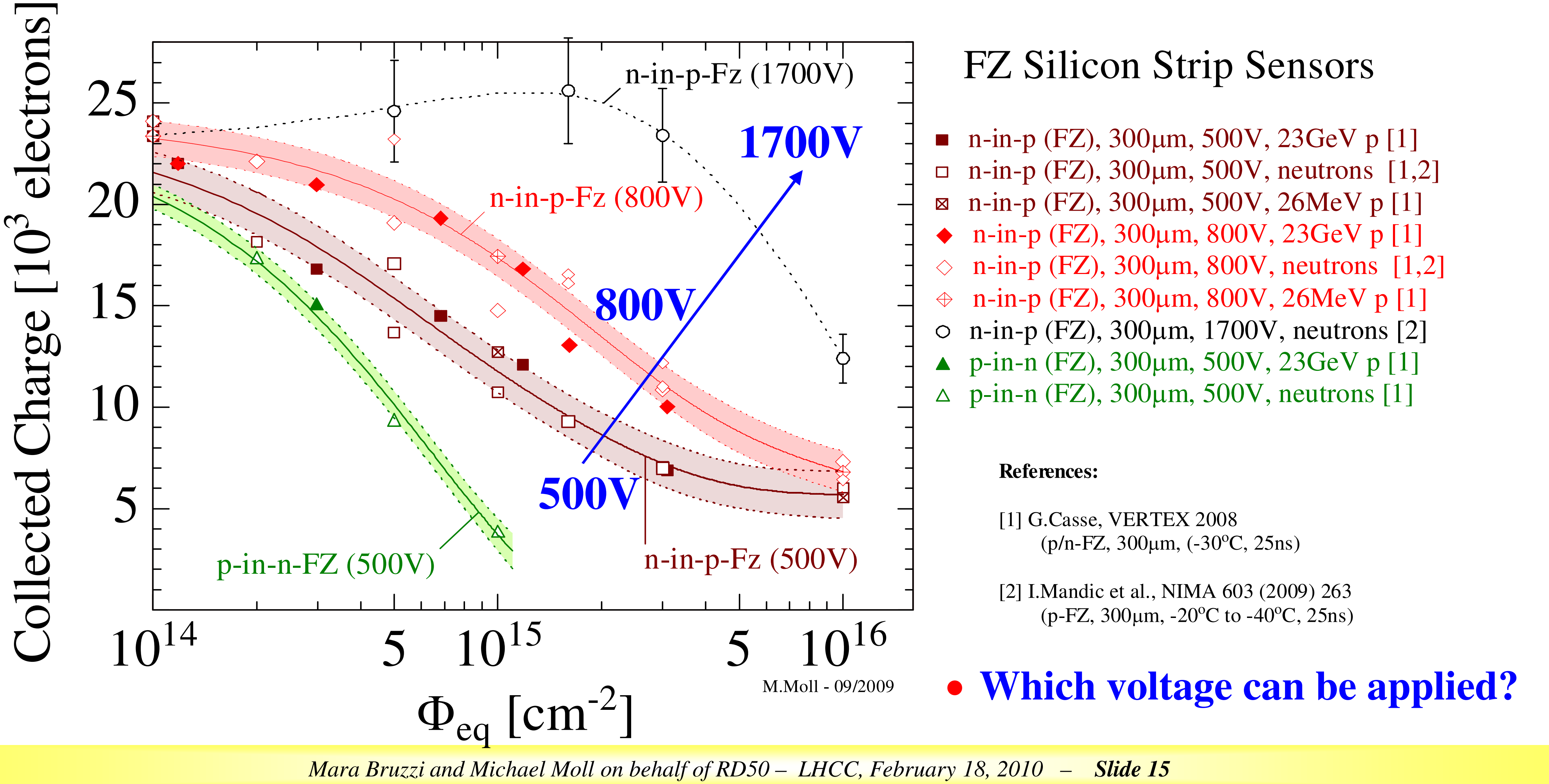


[S. Seidel, Vienna Conference on Instrumentation 2010]

- n-bulk (after type inversion)
  - Majority charge carriers: holes (smaller mobility than electrons)
  - Depletion zone builds from (unsegmented) back side → sensor must be fully depleted
- p-bulk
  - No type inversion via radiation
  - Majority charge carriers: electrons
  - Depletion zone builds from segmented side → can run underdepleted
  - Simpler single-sided processing
- n-in-p sensors serious candidate for ATLAS silicon strip detector upgrade

Sensors with p-Type Bulk

- Further (surprising) advantage of n-in-p FZ silicon
  - CCE shows not reverse annealing, even when underdepleted
  - Current interpretation: charge multiplication effects (not described by Hamburg model), even CCE > 1 for very high bias voltage (1700 V)
    → feasible in LHC experiments?



Summary

- Radiation damage to silicon sensors at hadron colliders
  - Equivalent fluences up to 10^{16} 1 MeV n per cm^2 in LHC high-luminosity phase
  - Major challenge for operating silicon detectors at hadron colliders
- Macroscopic consequences:
  - Change of effective charge carrier concentration → increased depletion voltage
  - Increase leakage current → more noise, thermal runaway
  - Reduced charge collection efficiency → smaller signals
- Microscopic understanding:
  - Point defects and clusters, some are electrically active
  - Laboratory measurements: I–V and C–V characteristics, DLTS, TSC, annealing
  - Phenomenological Hamburg model
- Active field of research: exploring new sensor types, production methods, and behavior at very high fluences

Additional Material

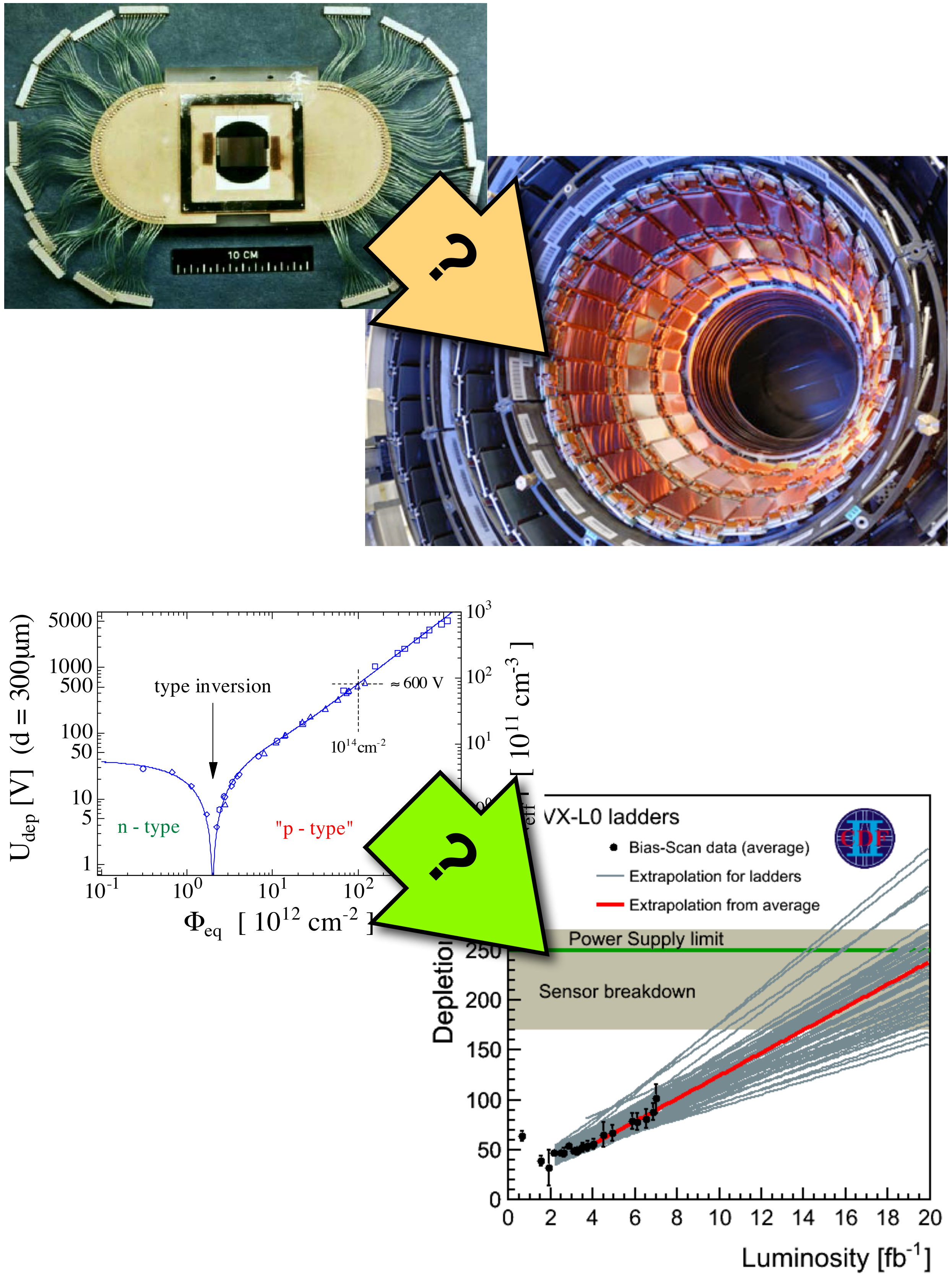
- The Hamburg connection
  - R. Wunstorf,
    Systematische Untersuchungen zur Strahlenresistenz von Silizium-Detektoren für die Verwendung in Hochenergiephysik-Experimenten,
    PhD Thesis, U Hamburg 1992
  - M. Moll,
    Radiation Damage in Silicon Particle Detectors,
    PhD Thesis, U Hamburg 1999
- CERN RD50 collaboration: http://www.cern.ch/rd50
- Books:
  - G. Lutz, *Semiconductor Radiation Detectors*, Springer, 2007
  - L. Rossi, P. Fischer, T. Rohe, N. Wermes, *Pixel Detectors*, Springer, 2006
  - S.M. Sze, *Physics of Semiconductor Devices*, Wiley, 1985

Fall School of the IRTG "Development and Application of Intelligent Detectors"
Heidelberg, November 1–5, 2010

Operating Silicon Detectors at Hadron Colliders

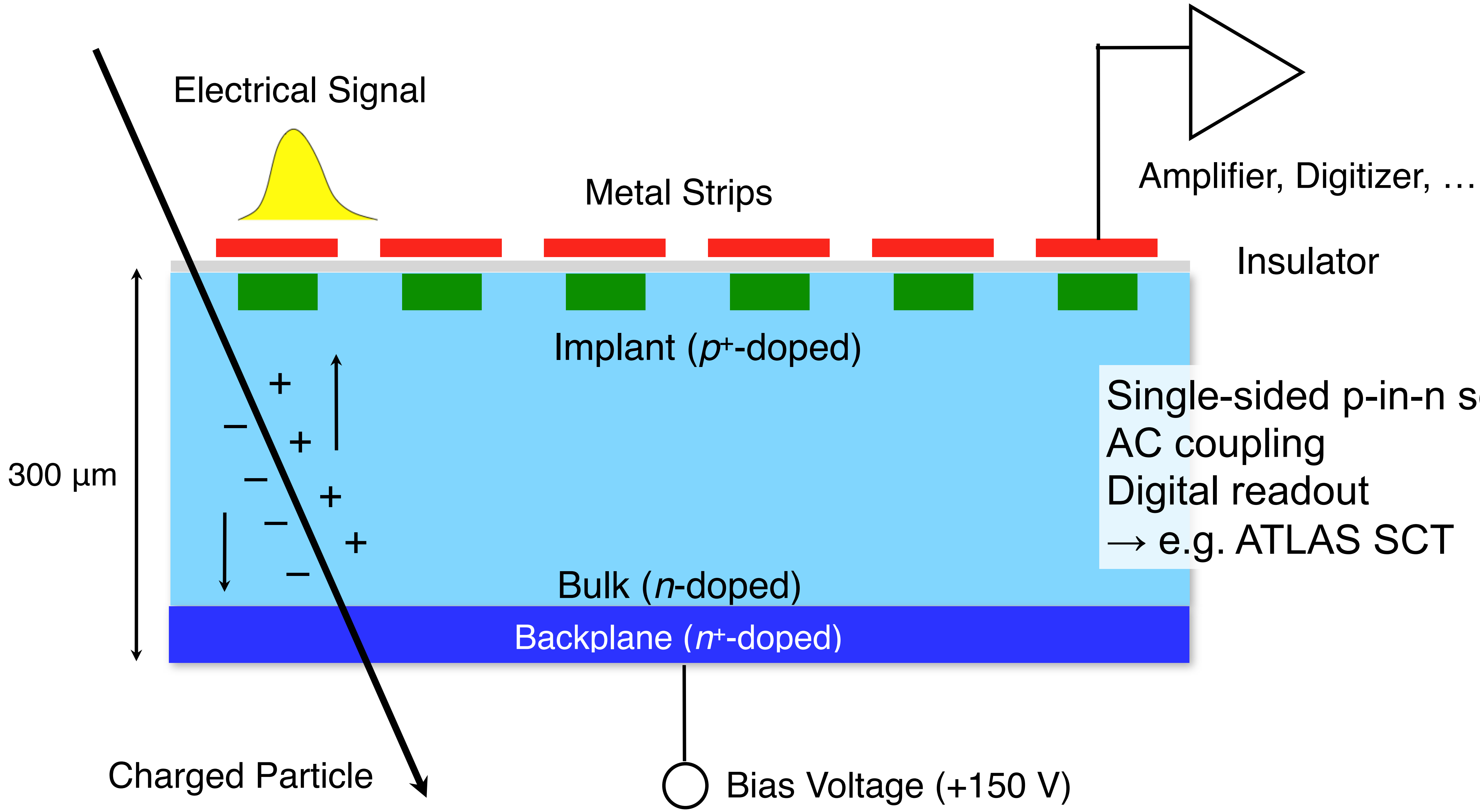
Ulrich Husemann
Deutsches Elektronen-Synchrotron DESY

Outline



- Short history of silicon detectors at hadron colliders
  - Evolving requirements and design considerations
  - Lessons learnt for the LHC and beyond
- In-situ measurement of radiation damage during operation
  - How can in-situ and laboratory measurements be compared?
  - Many examples taken from CDF experiment at Fermilab Tevatron (LHC only in its first year, difficult to find material)
- Mitigation of radiation damage

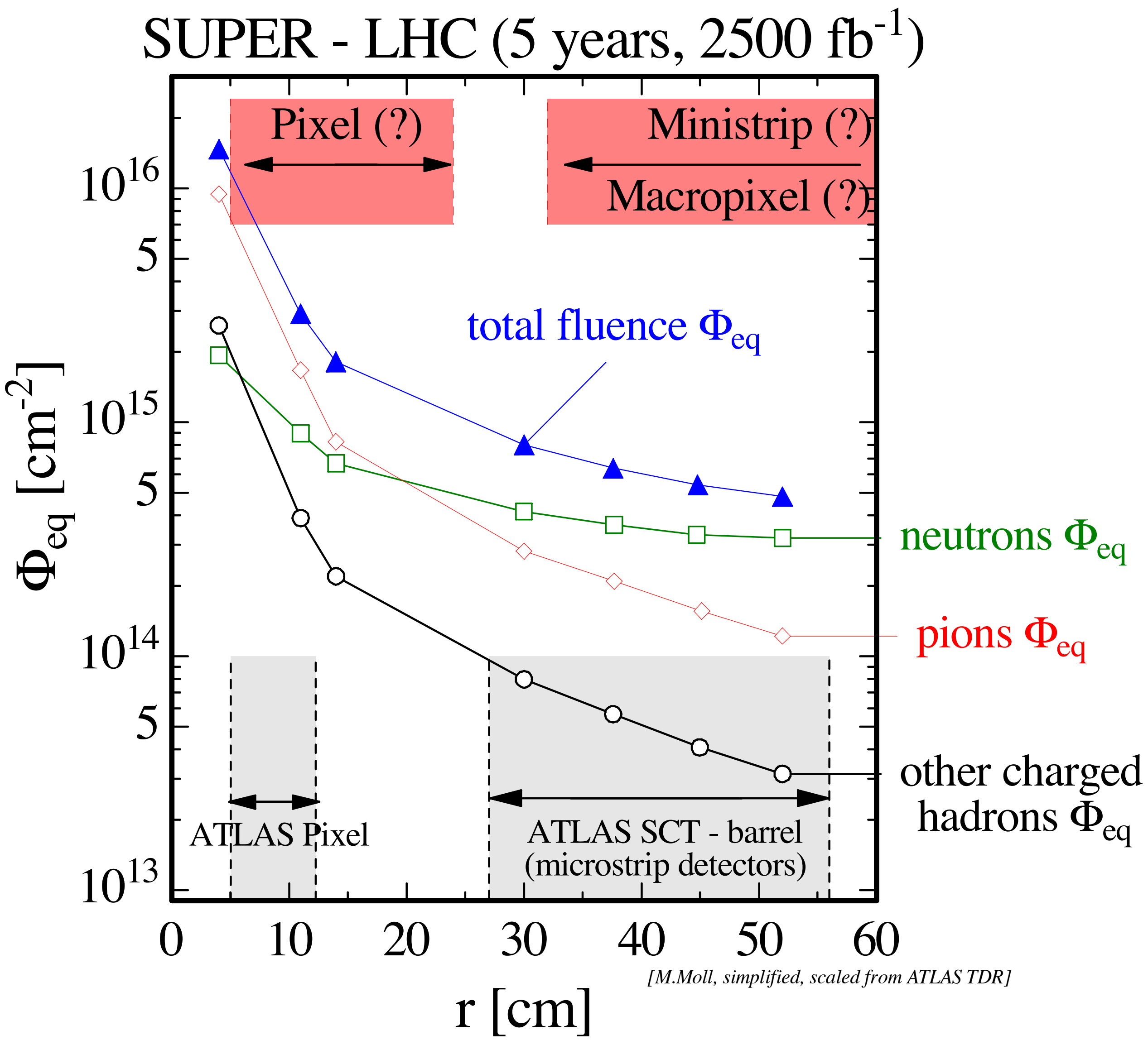
Short Reminder: Silicon Strip Detector



Single-sided p-in-n sensor
AC coupling
Digital readout
→ e.g. ATLAS SCT

- Variants of silicon strip detectors used at hadron colliders
  - One or both sides of the sensor segmented: single-sided vs. double-sided
  - DC coupling or AC coupling of readout system
  - Output of frontend chips: analog or digital readout

Short Reminder: Radiation Damage



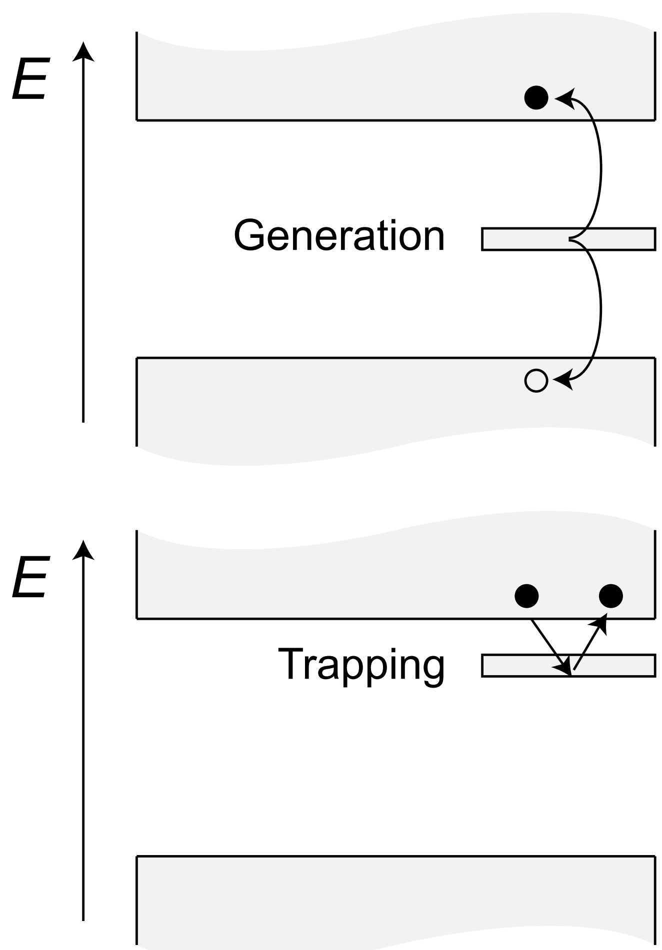
- Silicon bulk damage:
  - Displacement of atoms through non-ionizing energy loss (NIEL)
  - NIEL hypothesis: damage from all particle types scales with NIEL
  - NIEL normalized to fluence of 1 MeV neutrons with hardness factor κ

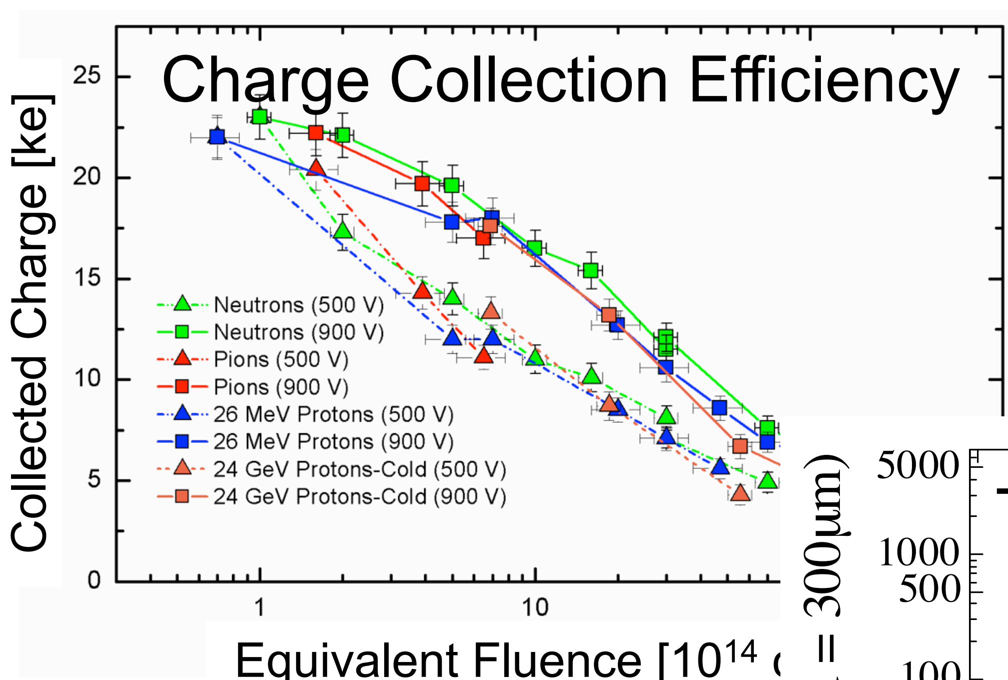
$$\Phi_{eq} = \kappa\Phi = \kappa \int \phi \, dE$$

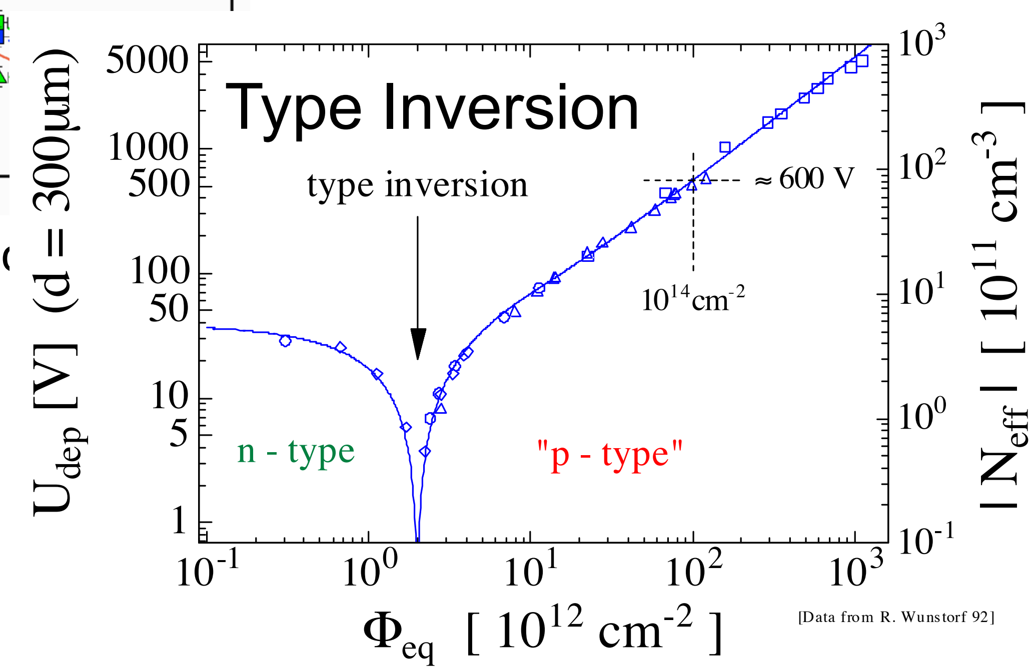
- Damage to silicon sensor surface and readout electronics
  - Driven by ionizing radiation dose
  - Reversible damage: single-event upsets (see lecture by Ketil Røed)
  - Irreversible damage: charge trapping at Si–SiO_2 interface (more in lecture by Ivan Peric)

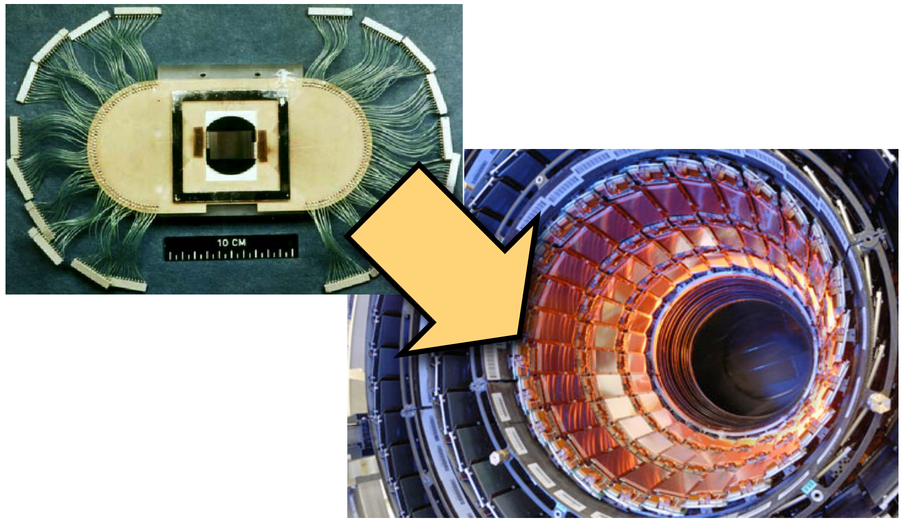
Short Reminder: Radiation Damage

- Microscopic effects and macroscopic consequences (simplified)
  - Deep level defects → bulk current generation → leakage current $\Delta I = \alpha\Phi$
  - Shallow level defects → charge trapping → lower charge collection efficiency
  - Shallow level defects as additional acceptor levels → change of effective charge carrier concentration → type inversion from n-bulk to (effective) p-bulk







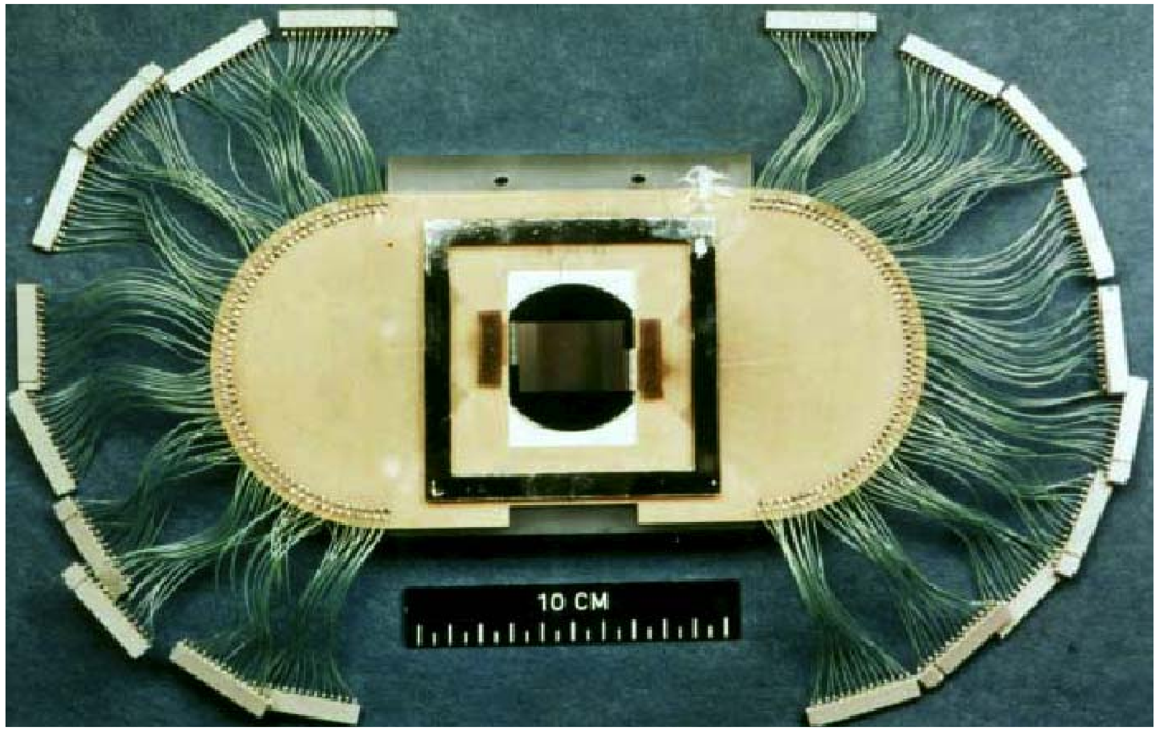


History of Silicon Detectors at Hadron Colliders

Silicon in HEP: A Little History

- Early history
  - 1951: first particle detector based on germanium pn-diode (McKay)
  - 1960ies–1970ies: semiconductor detectors important for nuclear physics
  - 1980: first silicon microstrip detector (J. Kemmer et al.)
- First particle physics application of silicon detectors: high-rate fixed target experiments for charm physics (esp. *D* meson lifetimes)
  - CERN NA11 (ACCMOR Collaboration): ~1983
  - Fermilab E691 (Tagged Photon Spectrometer): ~1985
- Silicon microstrip vertex trackers at electron-positron colliders (1990s)
  - All LEP detectors, Mark-II at SLC
  - *B* factories: BaBar, Belle

First Microstrip Detectors in Beam

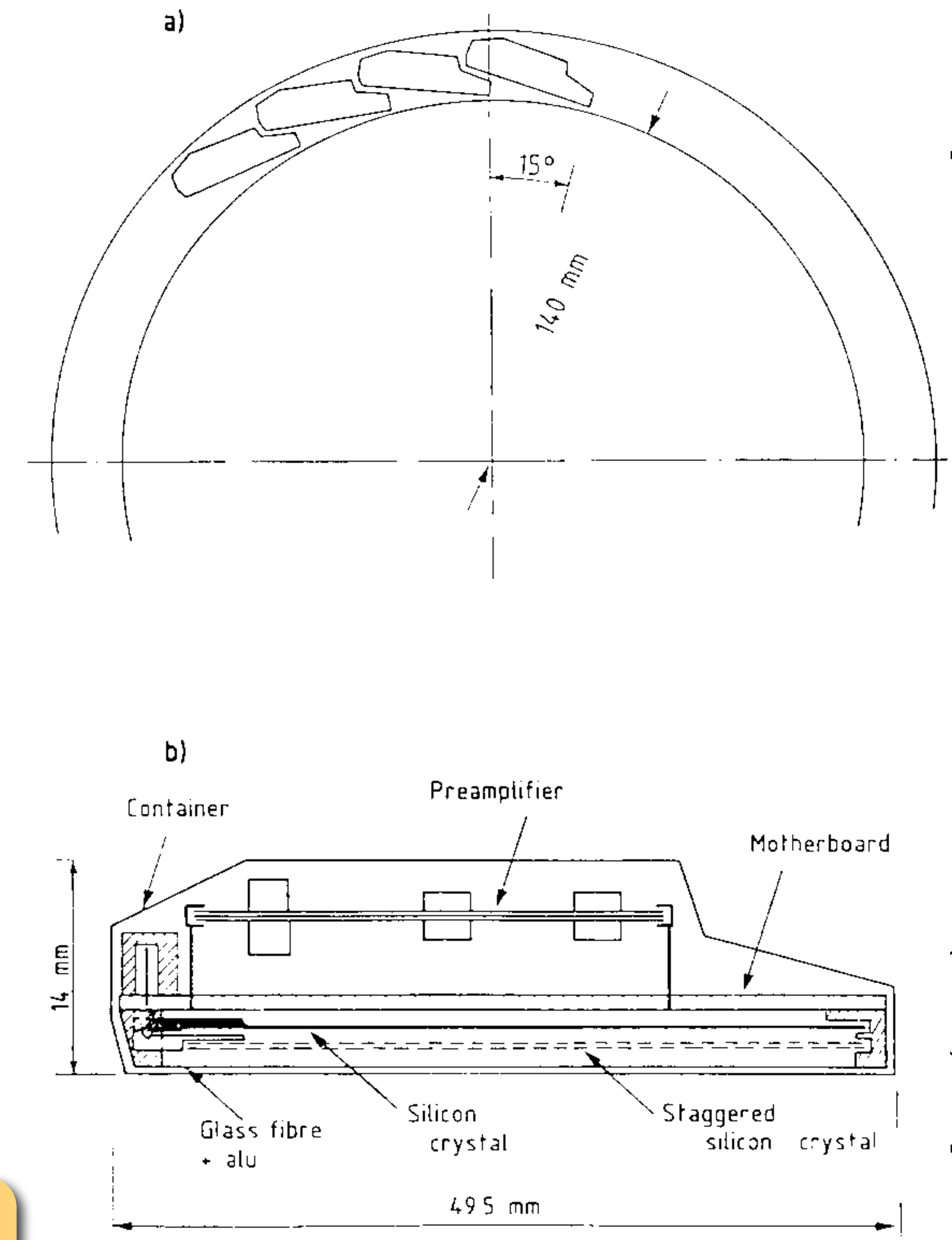


24 x 36 mm, 1200 strips
20 μm strip pitch
60 μm readout pitch

UA2 Silicon Pad Detector

- First application in a hadron collider (CERN Sp$\bar{p}$S)
  - Single cylinder of silicon pads (8.7 × 40 mm^2), 60 cm long, 14.7 cm radius, 1 m^2 of sensor surface
  - Mounted directly on the beam pipe
- First radiation damage
  - Beam incident during injection (unnoticed): exposure to 30 Gy of ionizing radiation + neutron flux of 2.8×10^9 cm^{-2}
  - Consequence: 14% noise increase through higher leakage currents
  - Today: sophisticated interlock systems to (largely) avoid beam incident

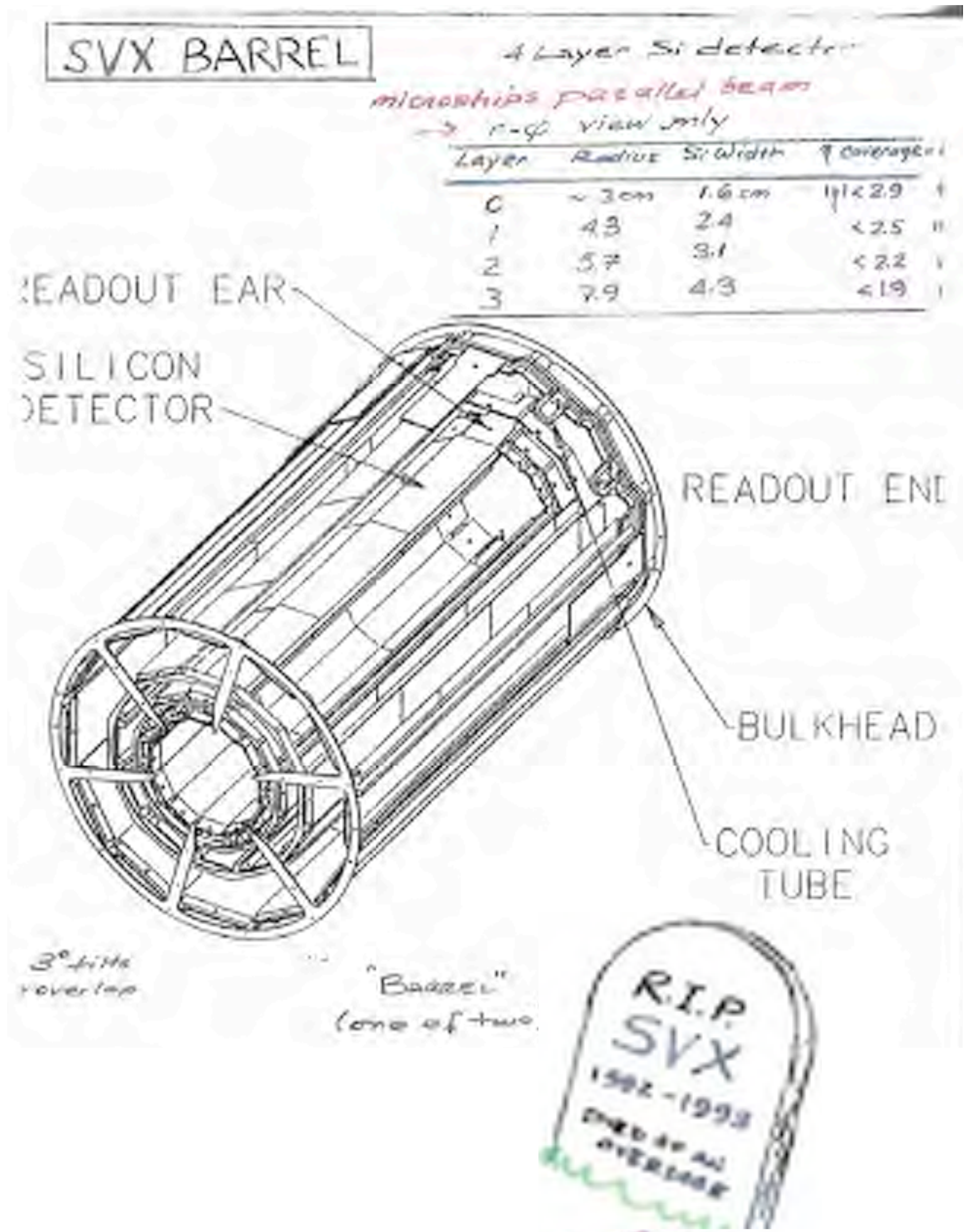
Significant damage through single incidents in addition to long-term radiation effects



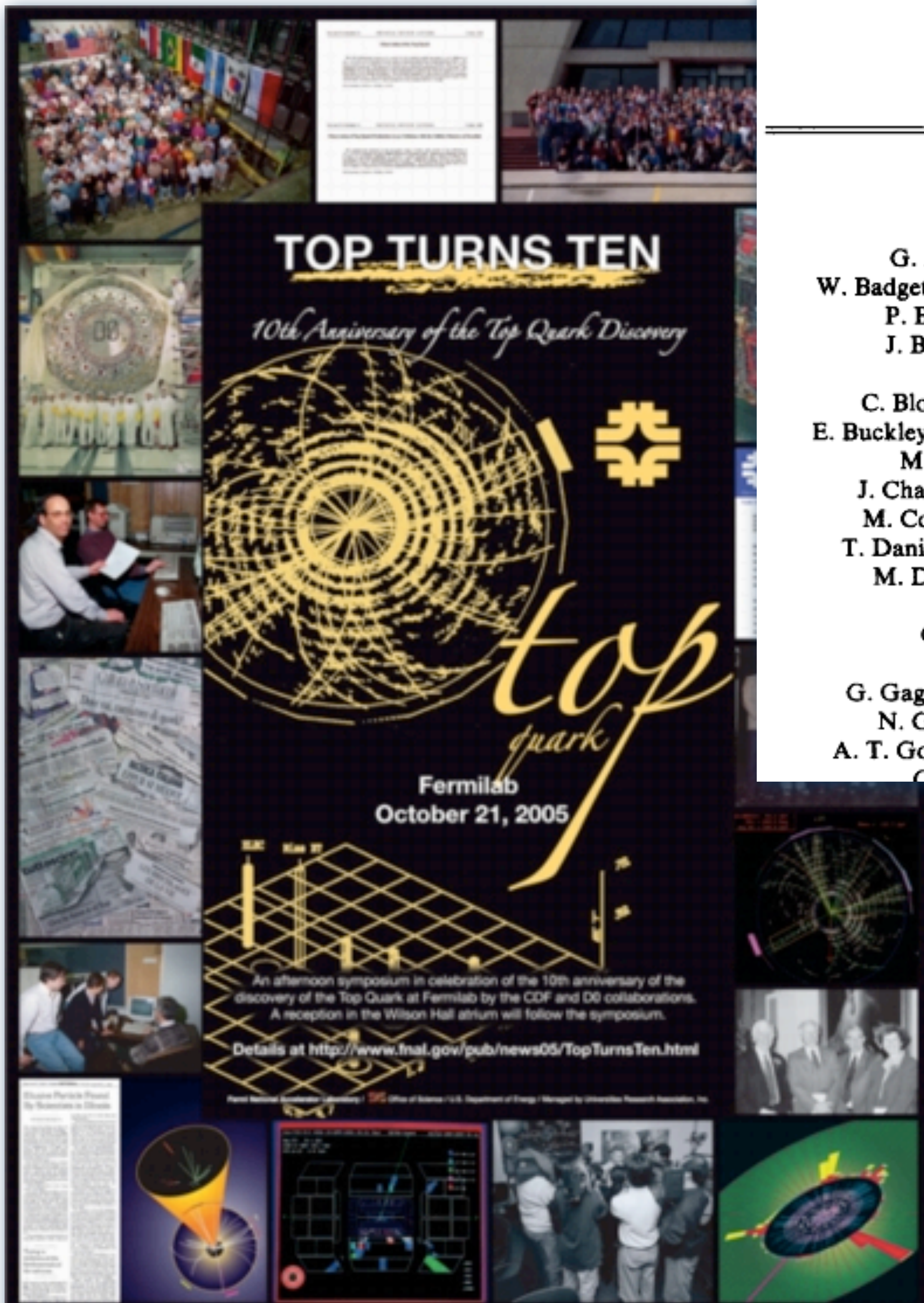
[R. Ansari et al., Nucl. Instrum. Meth. A279 (1989) 388]

Silicon Detector in CDF Run I a

- History:
  - First ideas in 1983 (A. Menzione)
  - Concept of silicon detectors at hadron colliders controversial within CDF (e.g.: occupancy of inner layers too high?)
- First design: SVX (1992–1993)
  - 2 barrels with 4 layers each, 51.1 cm long, radii: 3–8 cm
  - Single sided sensors (60 µm pitch), DC-coupled readout
  - Short lifetime mainly due to radiation damage to the readout chip: increased occupancy, reduced efficiency



> Electronics is the culprit this time
> → avoid single points of failure



PHYSICAL REVIEW D VOLUME 50, NUMBER 5 1 SEPTEMBER 1994

ARTICLES

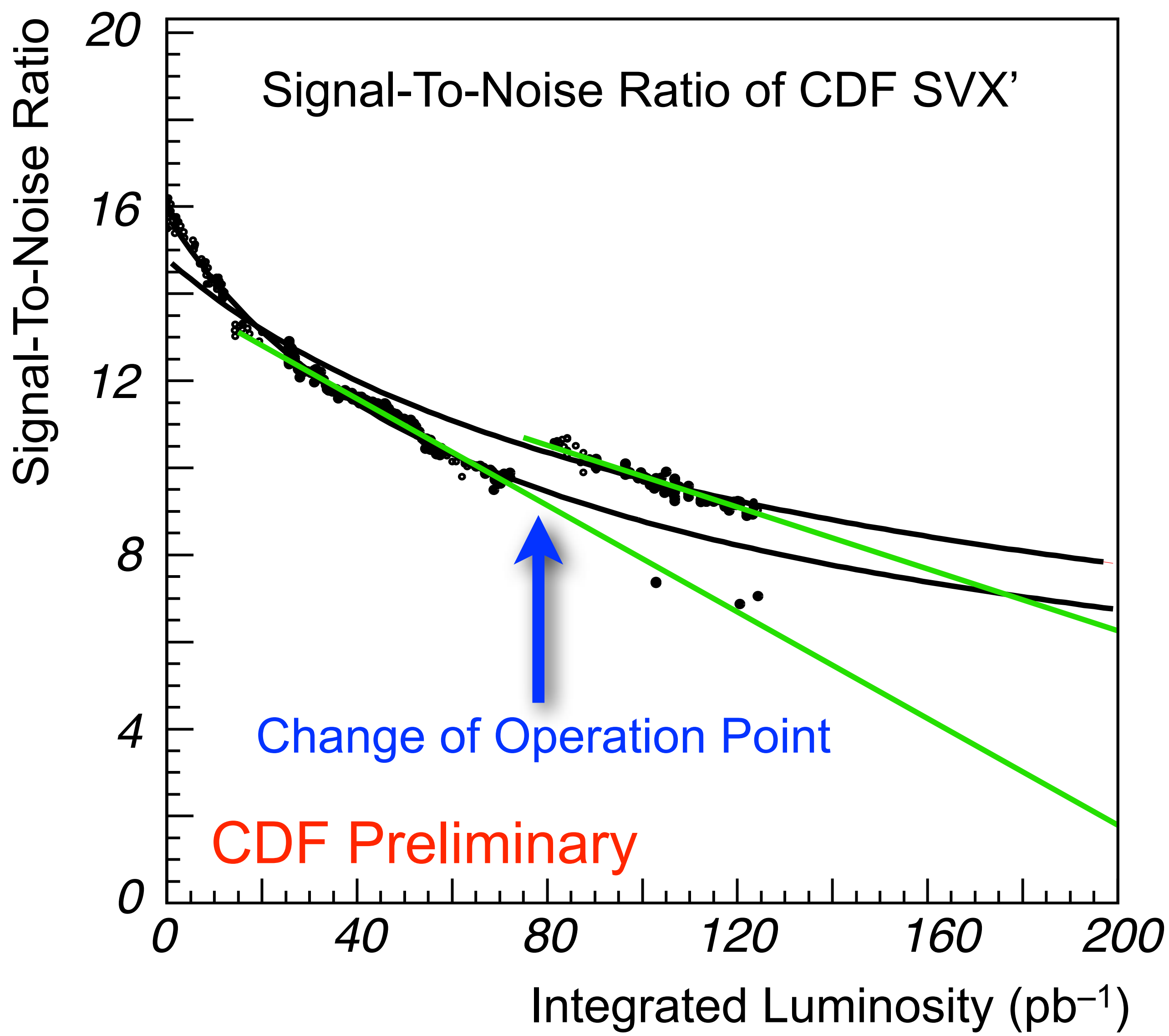
Evidence for top quark production in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV

F. Abe,[13] M. G. Albrow,[7] S. R. Amendolia,[23] D. Amidei,[16] J. Antos,[28] C. Anway-Wiese,[4] G. Apollinari,[26] H. Areti,[7] P. Auchincloss,[25] M. Austern,[14] F. Azfar,[21] P. Azzi,[20] N. Bacchetta,[18] W. Badgett,[16] M. W. Bailey,[24] J. Bao,[34] P. de Barbaro,[25] A. Barbaro-Galtieri,[14] V. E. Barnes,[24] B. A. Barnett,[12] P. Bartalini,[23] G. Bauer,[15] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[2] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[33] D. Benjamin,[32] J. Benlloch,[15] J. Bensinger,[2] D. Benton,[21] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[26] K. Biery,[11] M. Binkley,[7] F. Bird,[29] D. Bisello,[20] R. E. Blair,[1] C. Blocker,[29] A. Bodek,[25] V. Bolognesi,[23] D. Bortoletto,[24] C. Boswell,[12] T. Boulos,[14] G. Brandenburg,[9] E. Buckley-Geer,[7] H. S. Budd,[25] K. Burkett,[16] G. Busetto,[20] A. Byon-Wagner,[7] K. L. Byrum,[1] C. Campagnari,[7] M. Campbell,[16] A. Caner,[7] W. Carithers,[14] D. Carlsmith,[33] A. Castro,[20] Y. Cen,[21] F. Cervelli,[23] J. Chapman,[16] M.-T. Cheng,[28] G. Chiarelli,[8] T. Chikamatsu,[31] S. Cihangir,[7] A. G. Clark,[23] M. Cobal,[23] M. Contreras,[5] J. Conway,[27] J. Cooper,[7] M. Cordelli,[8] D. P. Coupal,[29] D. Crane,[7] J. D. Cunningham,[2] T. Daniels,[15] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[23] M. Dell'Orso,[23] L. Demortier,[26] B. Denby,[23] M. Deninno,[3] P. F. Derwent,[16] T. Devlin,[27] M. Dickson,[25] S. Donati,[23] R. B. Drucker,[14] A. Dunn,[16] K. Einsweiler,[14] J. E. Elias,[7] R. Ely,[14] E. Engels, Jr.,[22] S. Eno,[5] D. Errede,[10] S. Errede,[10] Q. Fan,[25] B. Farhat,[15] I. Fiori,[3] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[18] J. Freeman,[7] J. Friedman,[15] H. Frisch,[5] A. Fry,[29] T. A. Fuess,[1] Y. Fukui,[13] S. Funaki,[31] G. Gagliardi,[23] S. Galeotti,[23] M. Gallinaro,[20] A. F. Garfinkel,[24] S. Geer,[7] D. W. Gerdes,[16] P. Giannetti,[23] N. Giokaris,[26] P. Giromini,[8] L. Gladney,[21] D. Glenzinski,[12] M. Gold,[18] J. Gonzalez,[21] A. Gordon,[9] A. T. Goshaw,[6] K. Goulianos,[26] H. Grassmann,[6] A. Grewal,[21] G. Grieco,[23] L. Groer,[27] C. Grosso-Pilcher,[5] C. Haber,[14] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[33] R. M. Hans,[34] K. Hara,[31] B. Harral,[21]

…The Top!

Silicon Detector in CDF Run I b

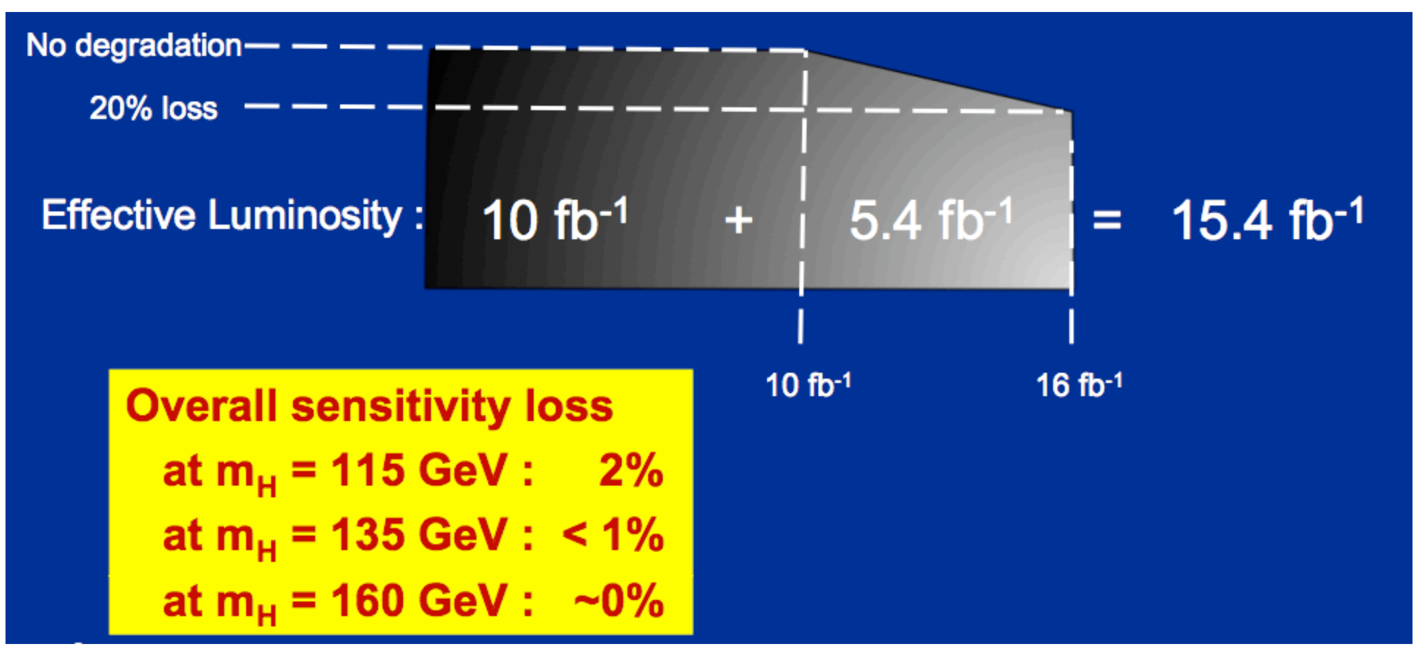
- Second attempt: SVX' (operated 1993–1996)
  - Mechanical design similar to SVX, slightly smaller inner radius (2.8 cm)
  - Radiation hard readout chip
  - AC-coupled readout with FOXFET (Field Oxide FET) biasing
- Lifetime limitation:
  - Signal-to-noise ratio (S/N) decreases faster than expected (attributed to FOXFET biasing)
  - Reduction of SNR partly compensated by changes in detector operation (integration time, temperature, bias voltage)



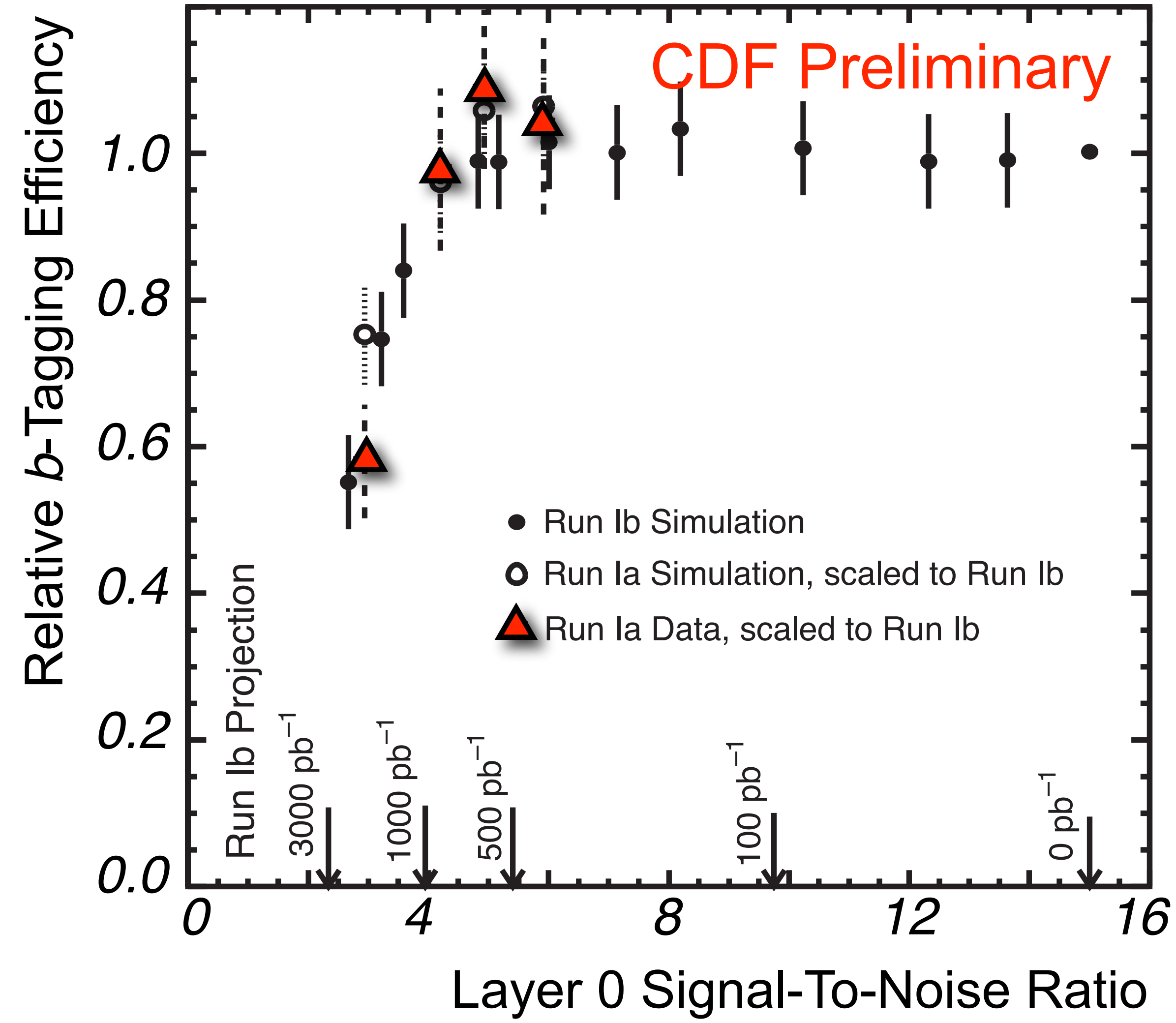
Some limitations can be overcome "after the fact" by clever software (written by clever people)

CDF Run I: Physics Impact

- Secondary vertex *b*-tagging and radiation damage
  - Efficiency drops quickly for S/N smaller than approx. 3
  - But: top quark discovery with data taken with S/N of 6 → 3
- Similar discussion ongoing for Higgs boson sensitivity in planned Tevatron Run III (2012–2015)



[G. Punzi, Fermilab PAC, September 2010]



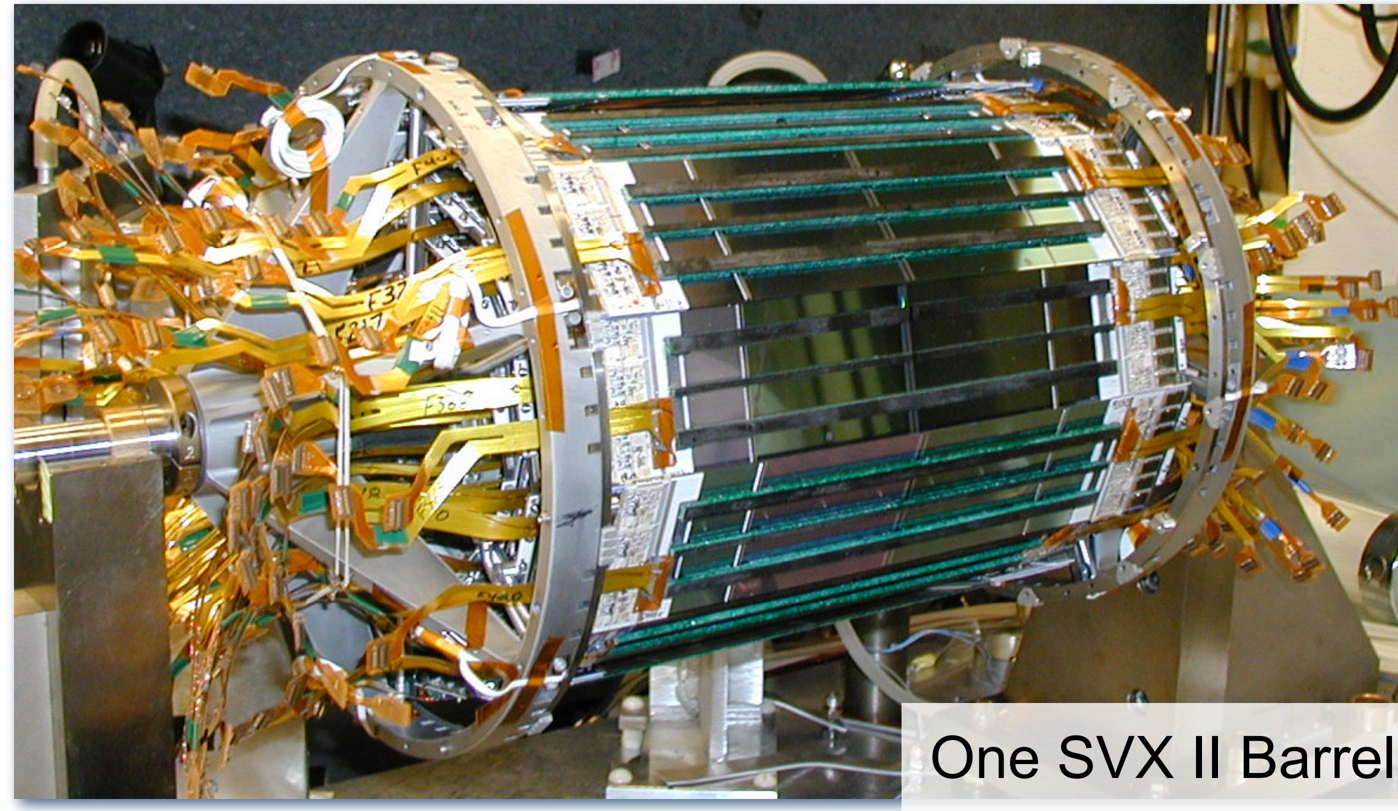
For more details on the history of Silicon detectors in CDF (and CMS):

J. Incandela, *Life on the Critical Path*

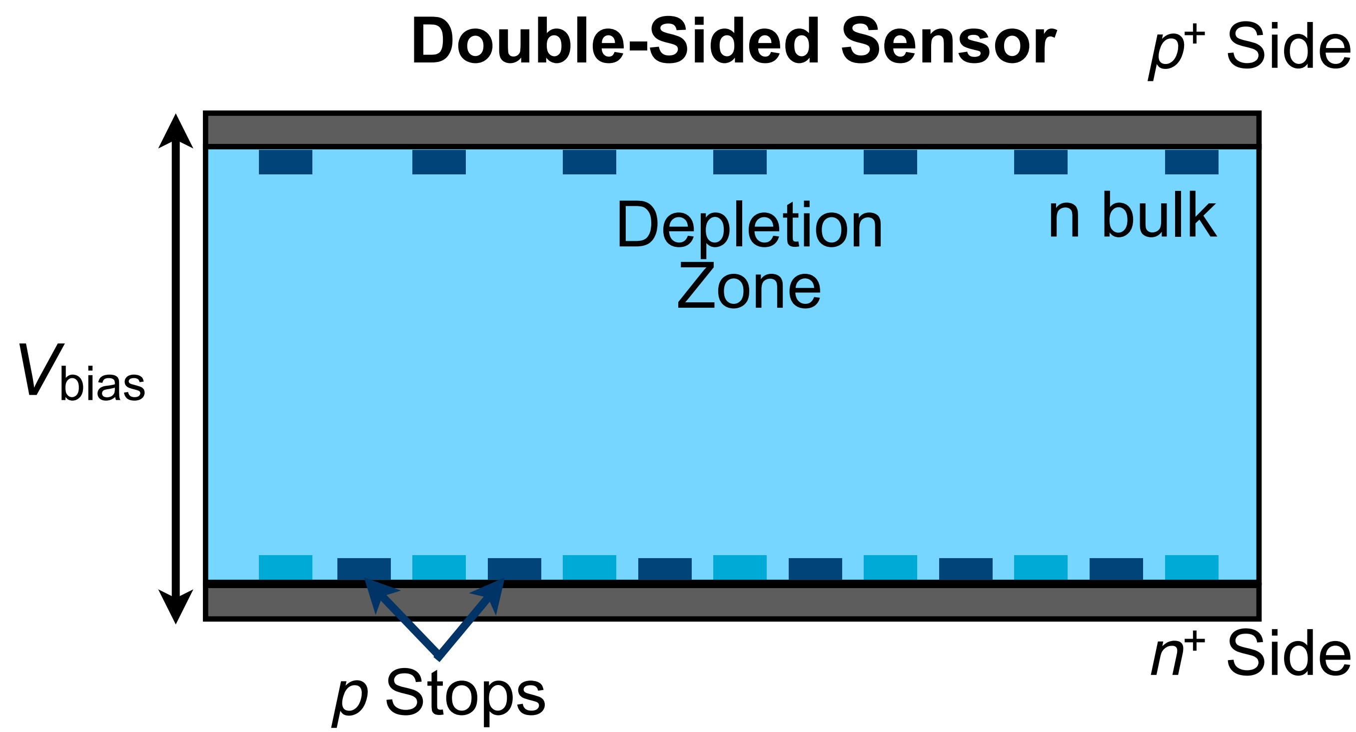
(talk given at the 6th International "Hiroshima" Symposium, Carmel, CA, September 11–15, 2006)

CDF SVX II: Double-Sided & AC-Coupled

- Workhorse for CDF silicon tracking in Tevatron Run II, operated since 2001
- Pre-LHC-era module design
  - 5 layers of double-sided silicon sensors at radii of 2.5–10.6 cm
  - Layers 0, 1, 3 (Hamamatsu): axial and 90º strips
  - Layers 2 and 4 (Micron): axial and 1.2º stereo strips
  - Strip pitch: 60–140 μm
  - AC-coupled readout: micro-discharges limit bias voltage to 170 V (Hamamatsu) and 80 V (Micron)
- More on performance & radiation hardness later

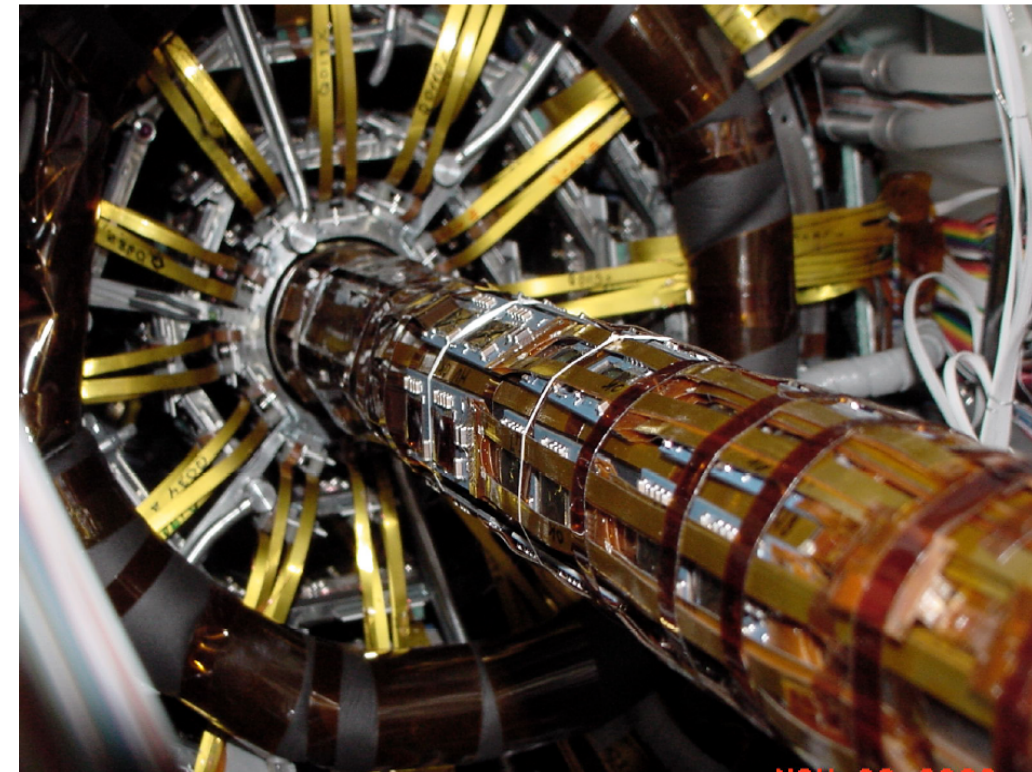

One SVX II Barrel

Double-Sided Sensor

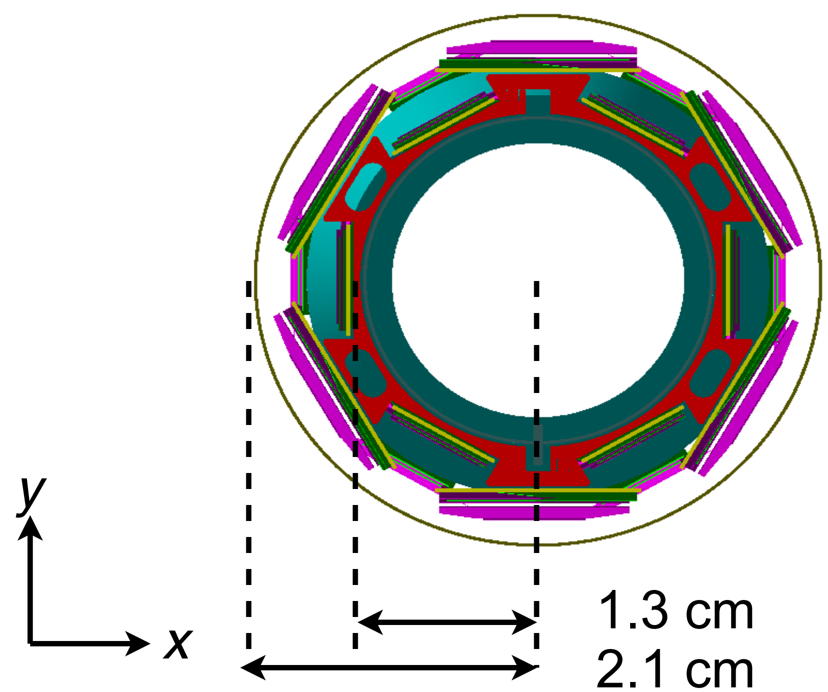


Towards LHC: Beam Pipe Layers

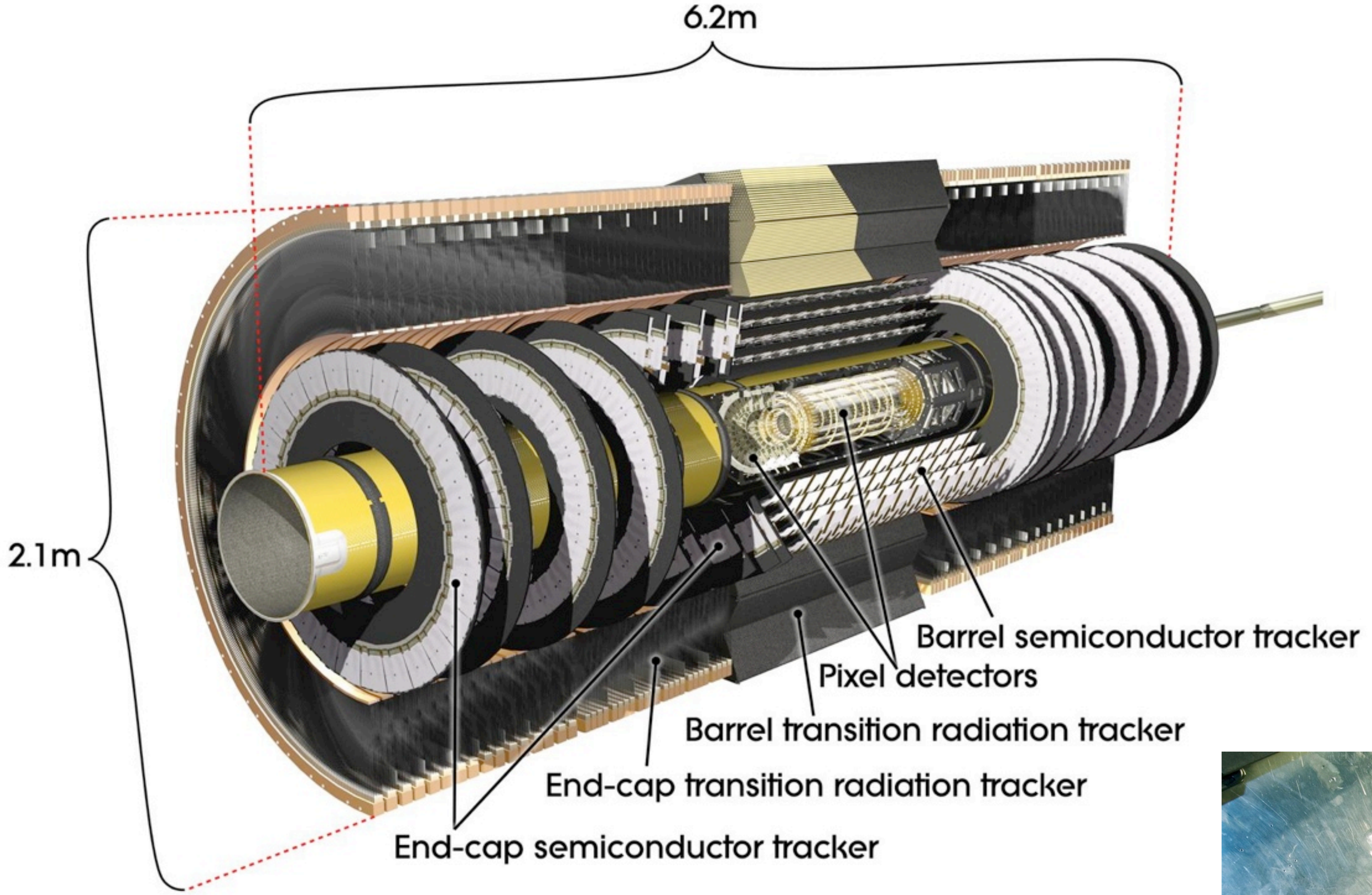
- Material and radiation considerations:
  - Below $r = 2$ cm, $0.01\ X_0$ of additional material does not matter, but track impact parameter resolutions increases greatly
  - Low material: remove readout electronics from tracking volume, transmit analog signals to chips → showed problems with pickup noise during operation
- Single-sided "LHC style" sensors (i.e. following LHC design rules) available:
  - "Regular" FZ sensors (Hamamatsu, SGS Thomson)
  - Oxygenated sensors (Micron) → believed to be more radiation hard
- DØ added a similar beam-pipe layer ("Layer 0") with improved readout (e.g. new SVX4 readout chip) in 2006

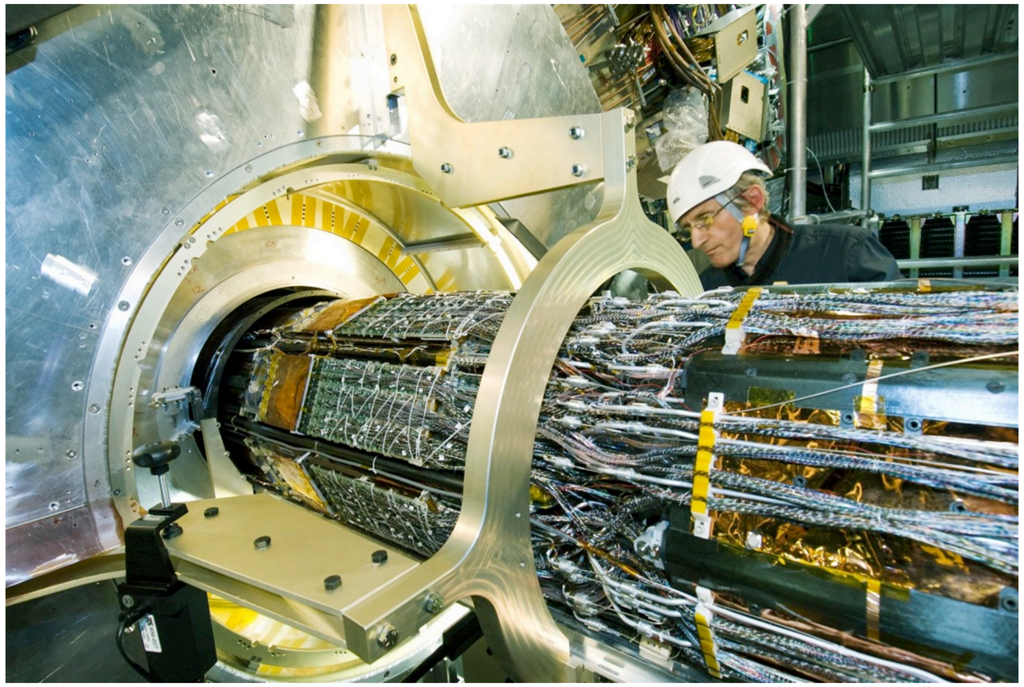


Insertion of L00: 300 µm clearance!



ATLAS Inner Tracking

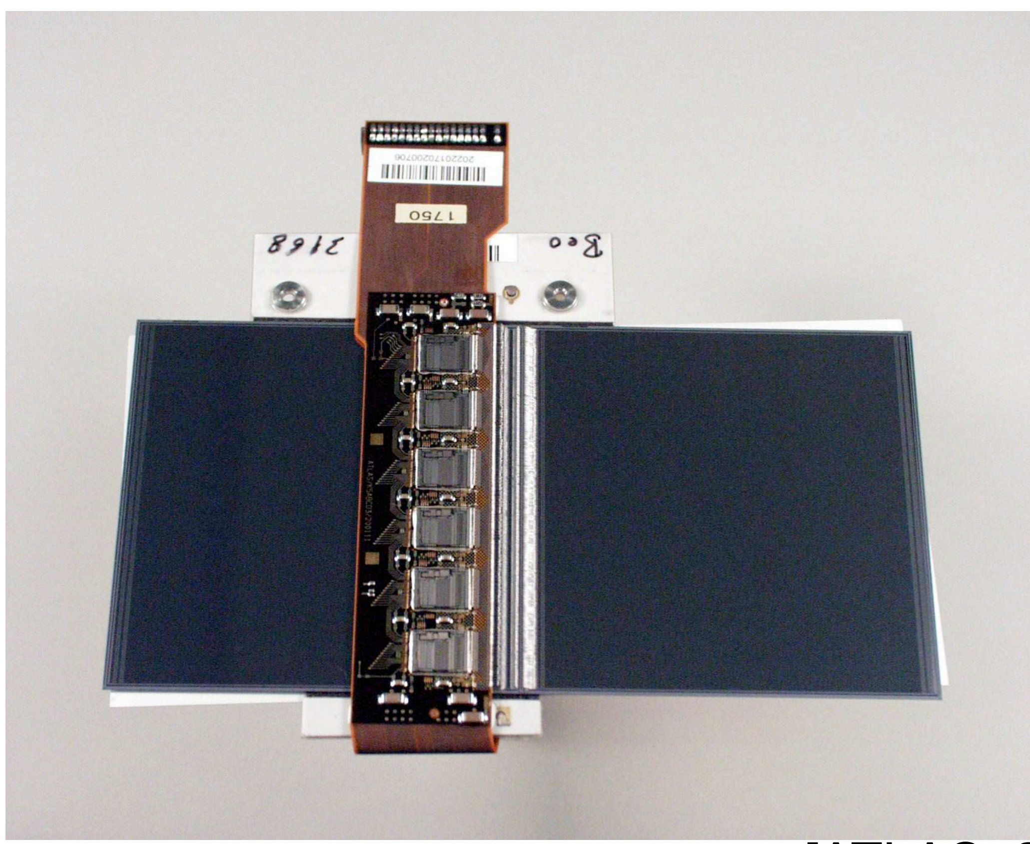


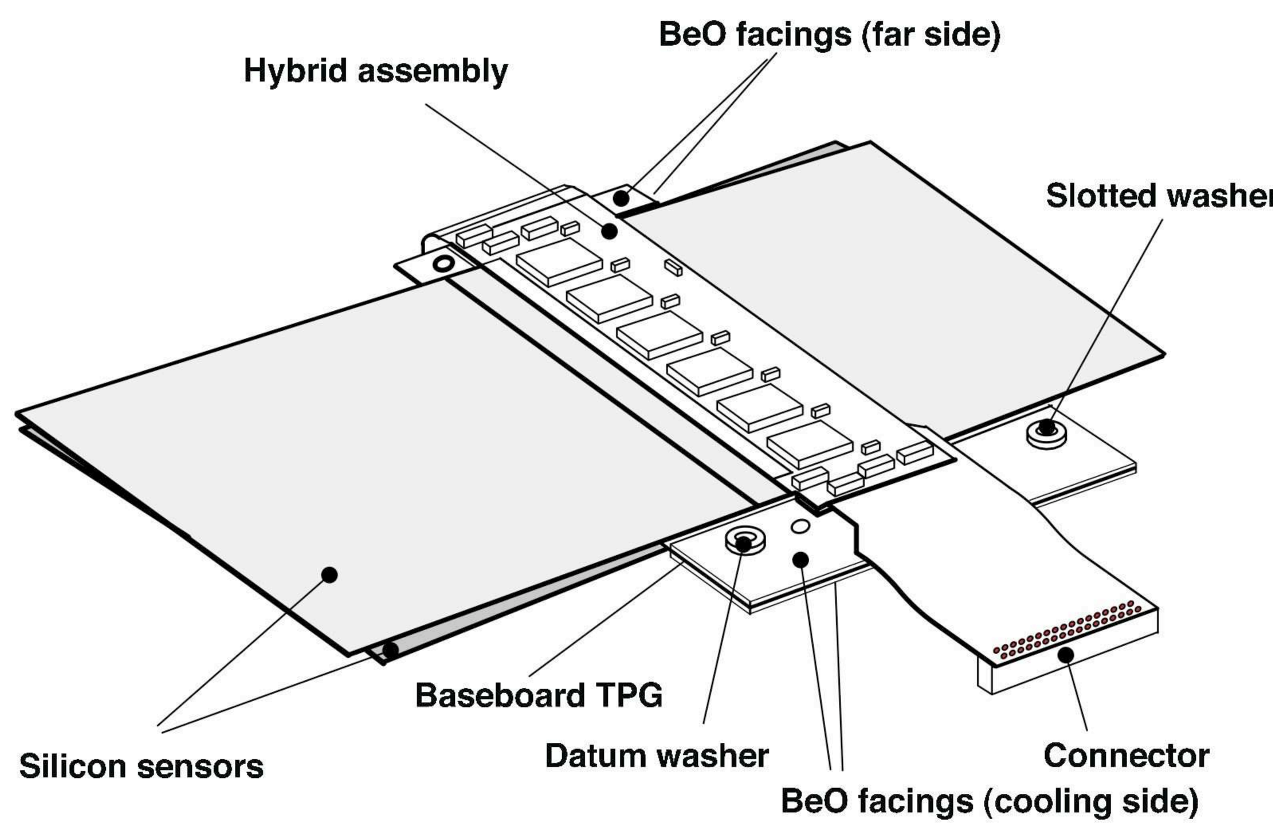


[atlas.ch]

ATLAS Semiconductor Tracker

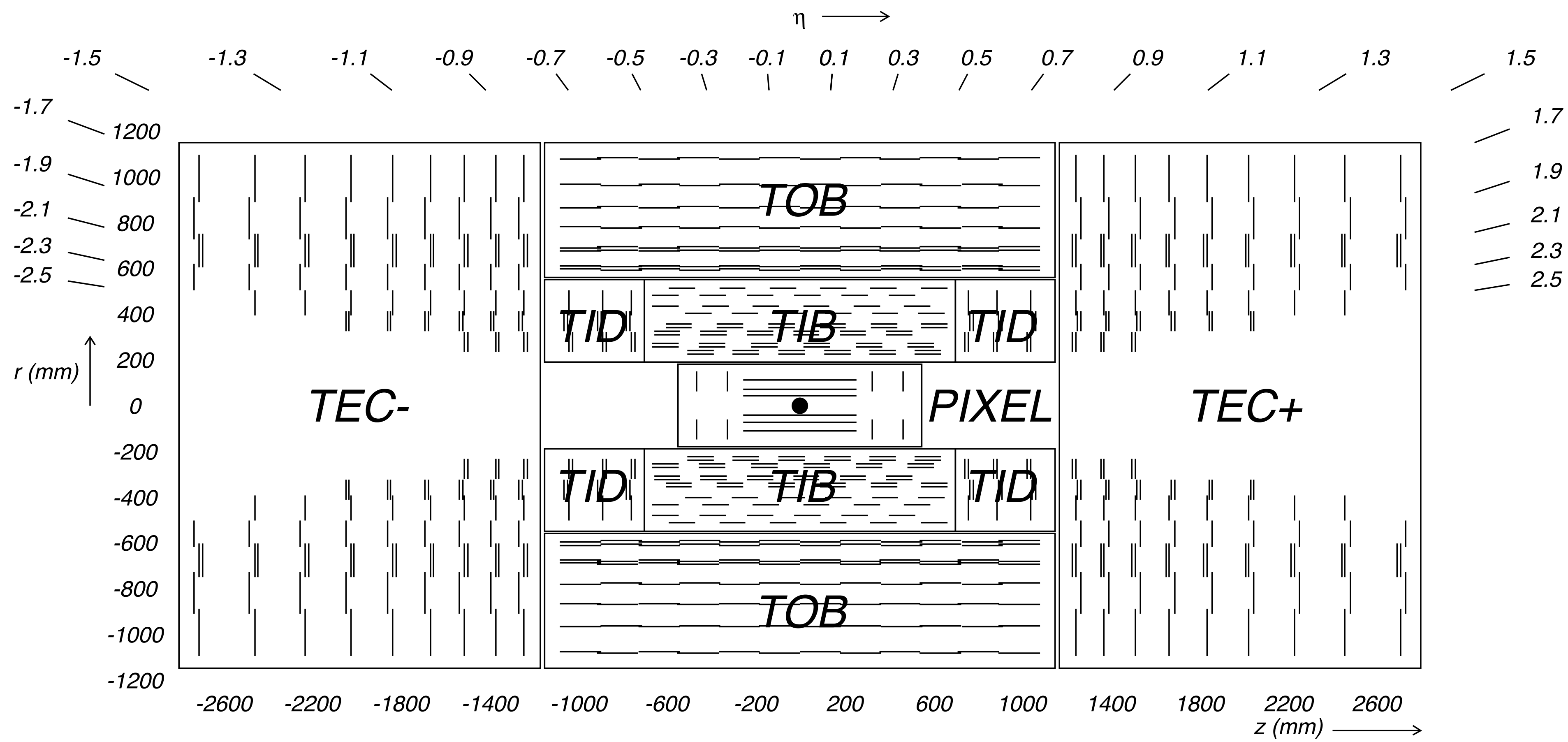
- Sensor and module design:
  - Sensor: single-sided p-in-n, AC coupled, 285 µm thick, strip pitch: 80 µm
  - Module: 2×2 sensors (6×6 cm^2 each) glued back to back, stereo angle of ±20 mrad
  - Binary readout (i.e. digital readout stripped down to “hit–no hit”)
- Radiation hardness: survive 10 years of LHC operation → designed to run stably at 500 V after $\phi_{eq} = 2\times10^{14}$ cm^{-2} (initial bias voltage: 150 V)

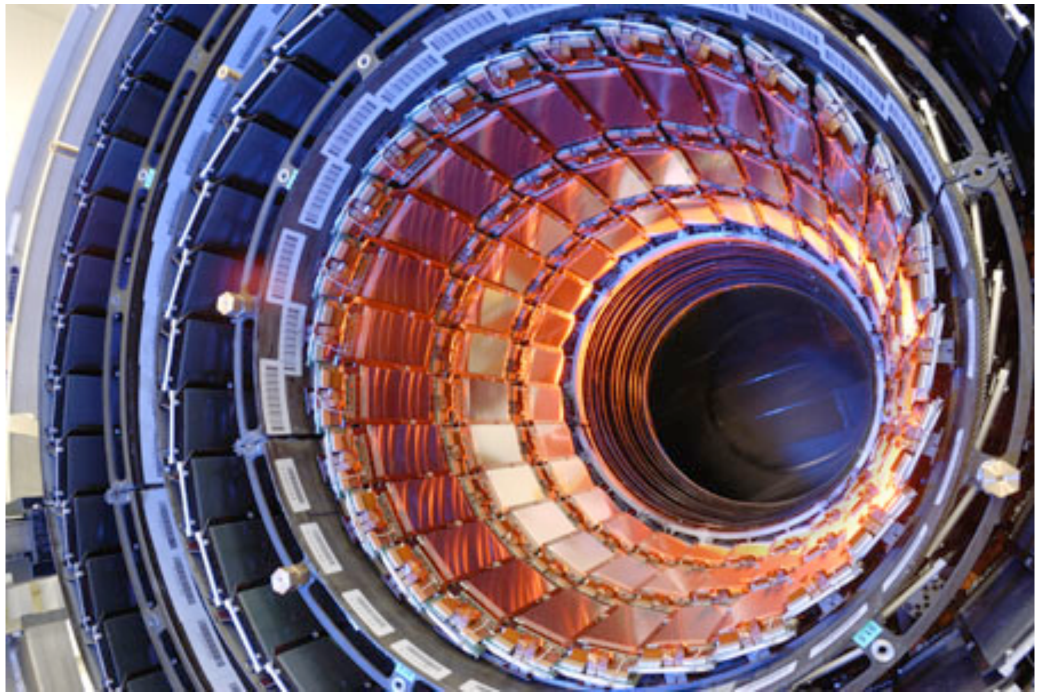




[ATLAS, 2008 JINST 3 S08003]

CMS Inner Tracking



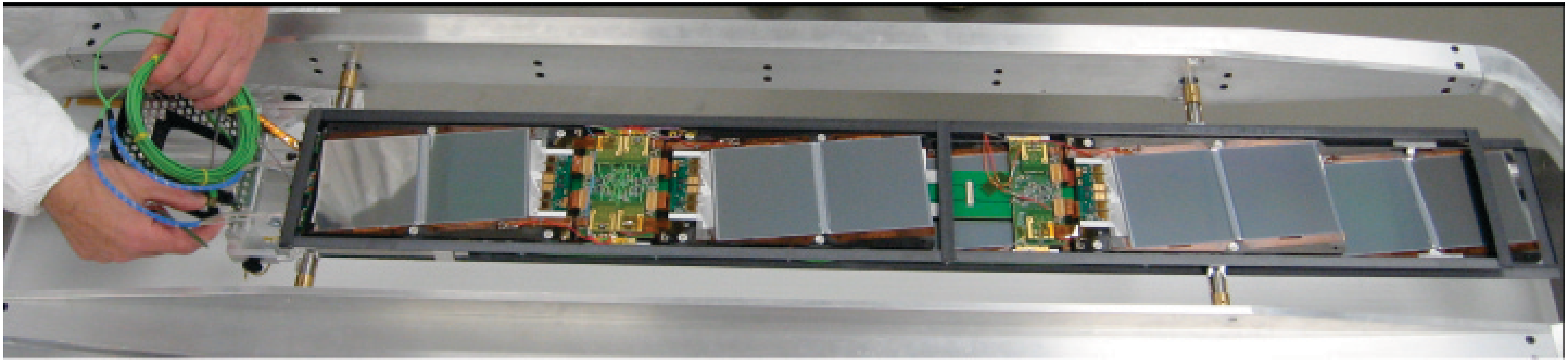


[http://cms.web.cern.ch/]

CMS Tracker

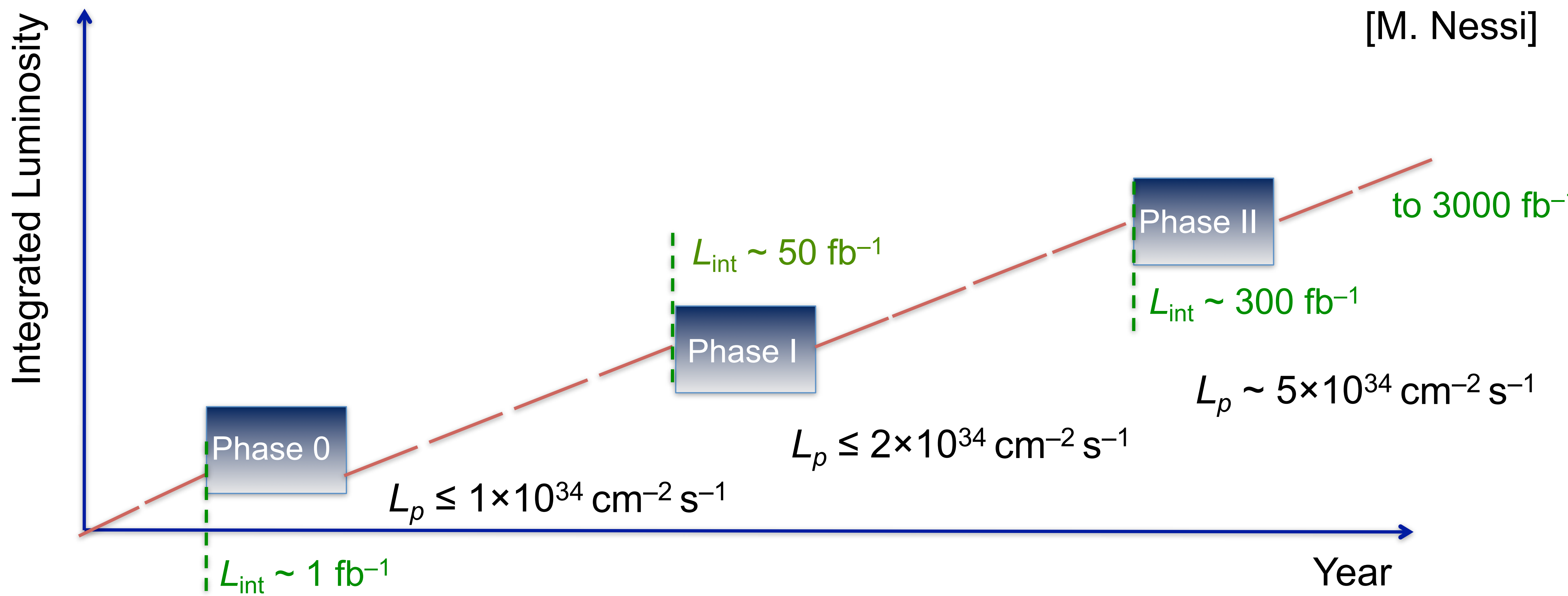
- Sensor and module design:
  - Sensor: single-sided p-in-n, AC coupled, 320/500 µm thick, varying strip pitch (two innermost inner and outer layers: double layers with 100 mrad stereo angle)
  - Modules: 1 thin sensor in inner and 2 thick sensors in outer part (10×10 cm^2 each)
  - Analog readout at front-end chip, digitized outside tracking volume
- Radiation hardness: survive 10 years of LHC operation ≈ 500 fb^{-1} ≈ 2×10^{14} cm^{-2} 1 MeV neutron equivalents

CMS Tracker Outer Barrel Rod



[CMS, 2008 JINST 3 S08004]

LHC Upgrade Roadmap

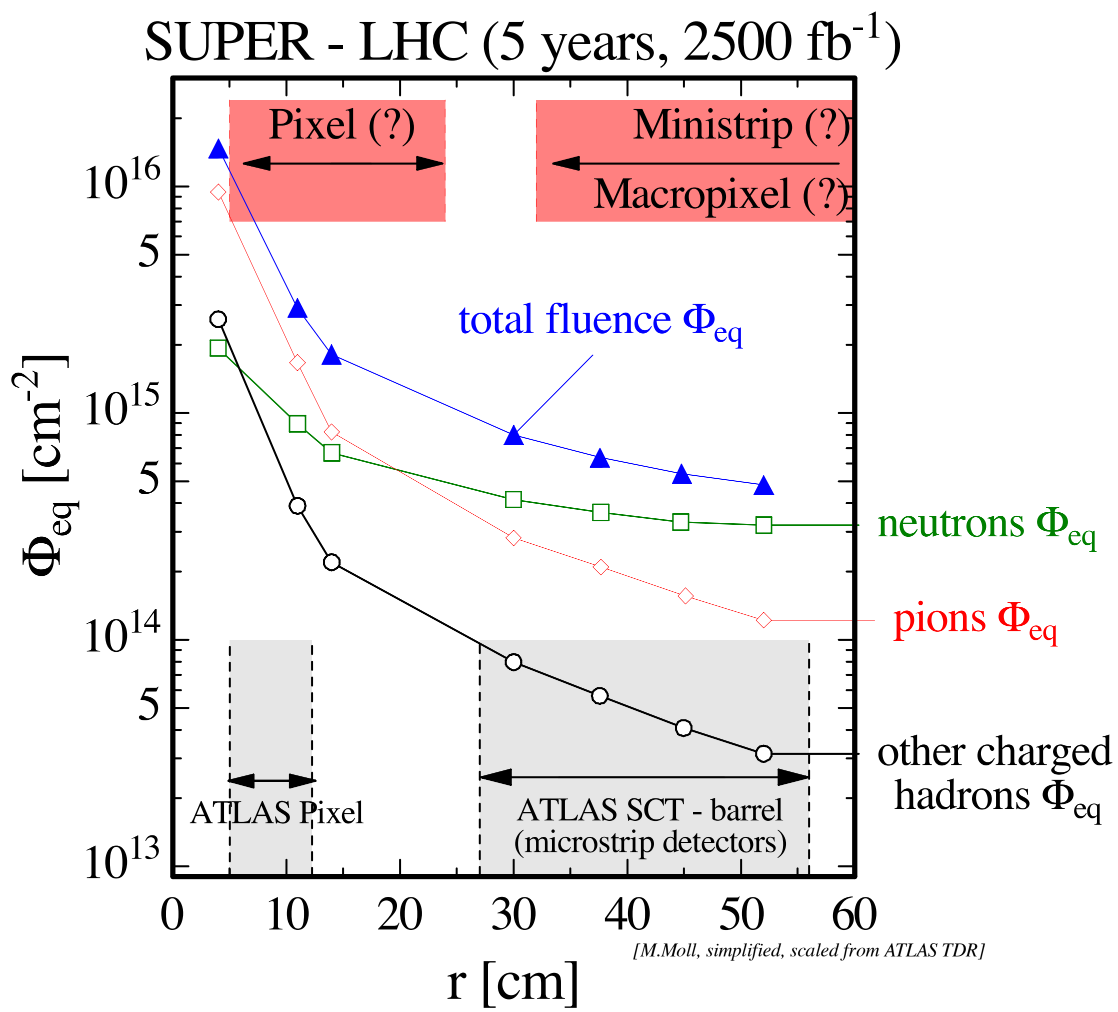


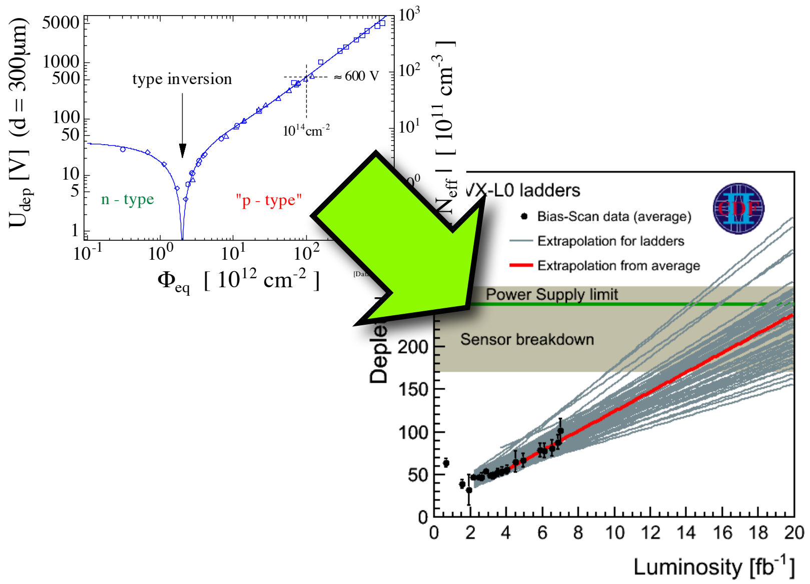
- LHC long-term perspective: 3000 fb^{-1} by 2030
  - Phase 0 (2012): energy increase to 13–14 TeV
  - Phase I (~2015): moderate luminosity increase
  - Phase II (~2020): high-luminosity phase ("LHC-HL", formerly known as Super-LHC)

ATLAS/CMS Upgrade Plans

	ATLAS	CMS
Phase I (2015)	New innermost pixel layer	Replacement of pixel detector
LHC-HL (2020)	Replacement of full inner detector with all-silicon tracker	Replacement of full silicon tracker

- New technologies considered for innermost pixel detector layers
  - 3D silicon
  - Diamond: “intrinsically radiation hard”
- Evolution of established technologies
  - Planar hybrid pixel detectors to cover large areas with pixels
  - n-in-p strip detectors: more radiation hard





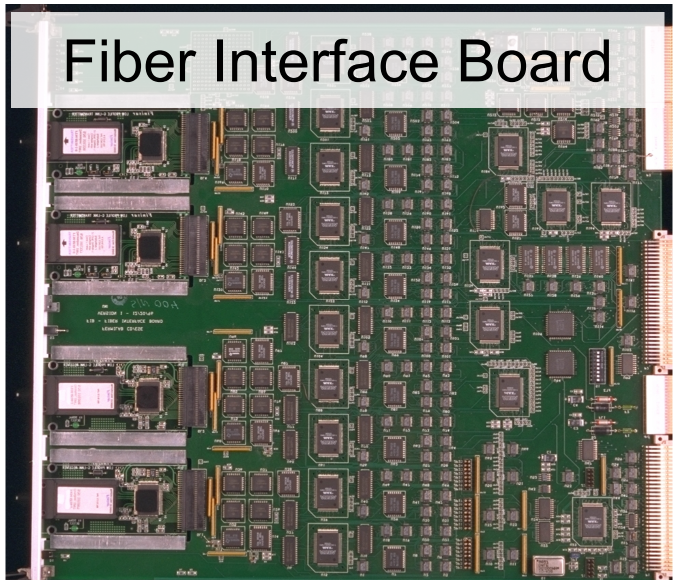
Radiation Damage and Running Experiments

Challenges in a Running Experiment

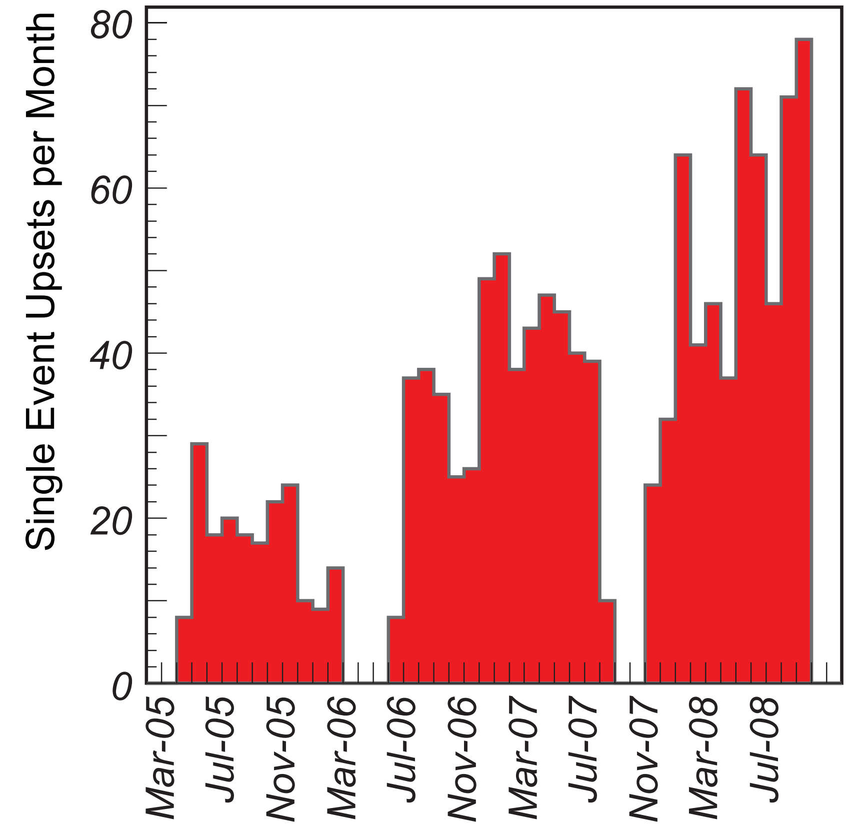
Issue	Ideal Environment	Running Experiment
Radiation monitoring	Take monitoring data as often as required	Must sacrifice good data to monitor detector performance
Measurement environment	Controlled lab environment (temperature, …)	Environment cannot be fully controlled, e.g. insufficient instrumentation
Accessibility of components	Lab: everything accessible	Most of detector inaccessible

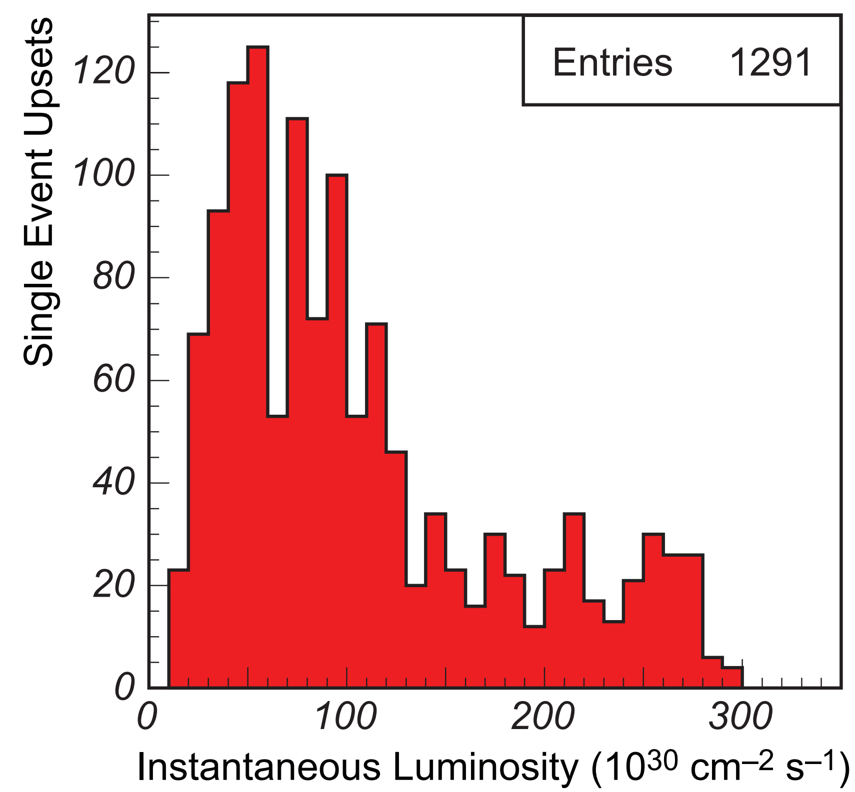
In the following: some real-life examples from the CDF silicon detectors (thanks to the CDF Silicon Operations Group for the material!)

CDF: Single Event Upsets



- Part of DAQ located in collision hall:
  - 58 Fiber Interface Boards (9U VME, 17 Altera 7128 FPGAs each)
  - FIBs contain “sequence RAM” for sequence of chip commands





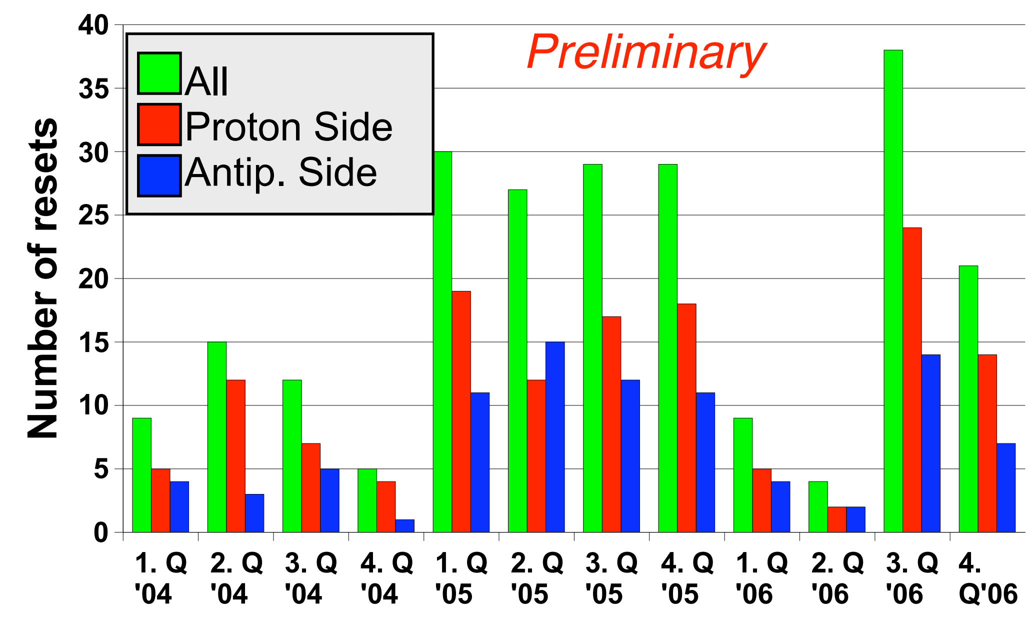
[UH, Proc. IEEE NSS 2008]

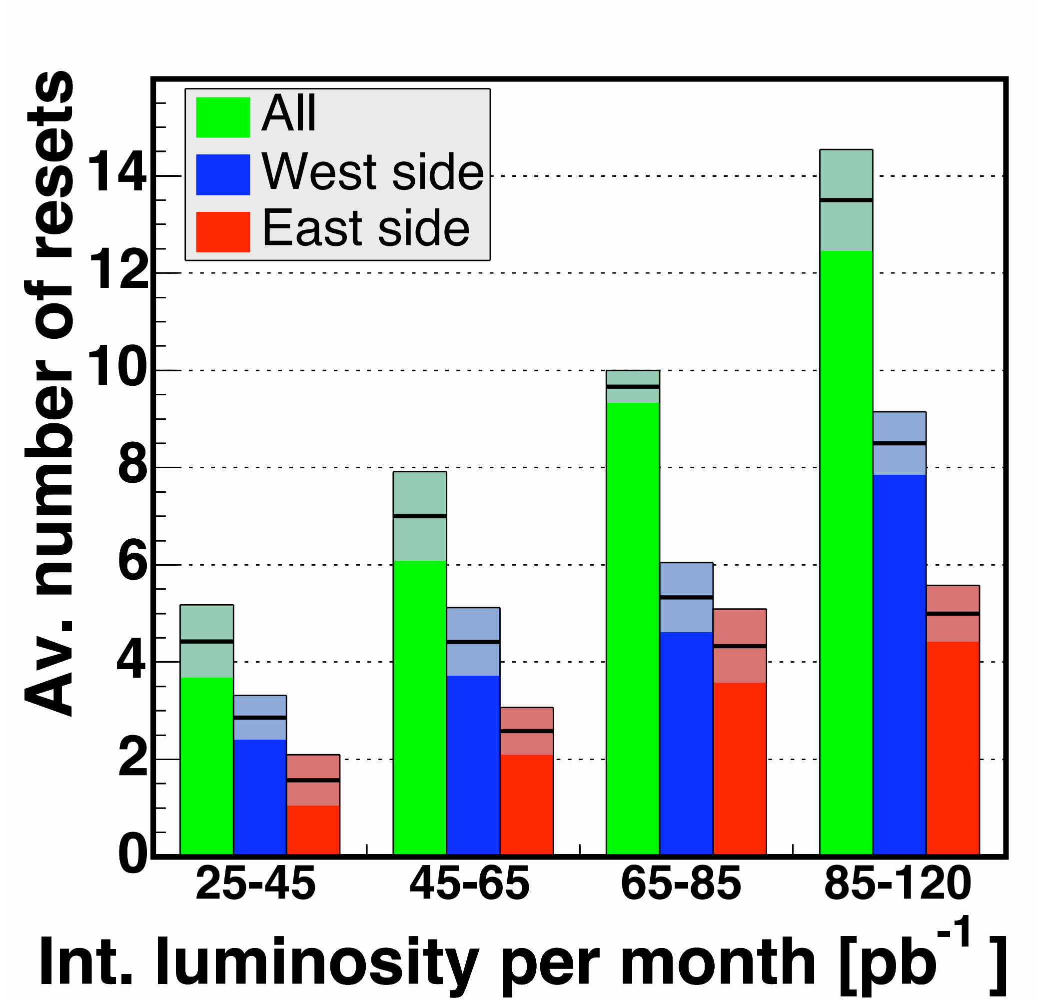
- DAQ problems due to single event upsets:
  - FIB sequence RAM corruption (1 per day): mostly unnoticed, sometimes corrupted data
  - FPGA burn-out on FIB (1–2 per year): VME backplane blocked

Keep sensitive electronics out of the experimental hall (if you can!)

CDF: Power Supplies

- Common failure modes of CAEN SY527 main frame:
  - Spontaneous switch-off and reboot of CPU
  - CAENnet communication loss
  - Corrupted read-back of currents/voltages
- Short-term fix: reboot ("Hockerize™") crate CPU
- Problems most probably beam-related:
  - Failure rate increases with increasing luminosity (and losses?)
  - Crates in areas with higher radiation dose (west side = proton side) seem to be more likely to fail

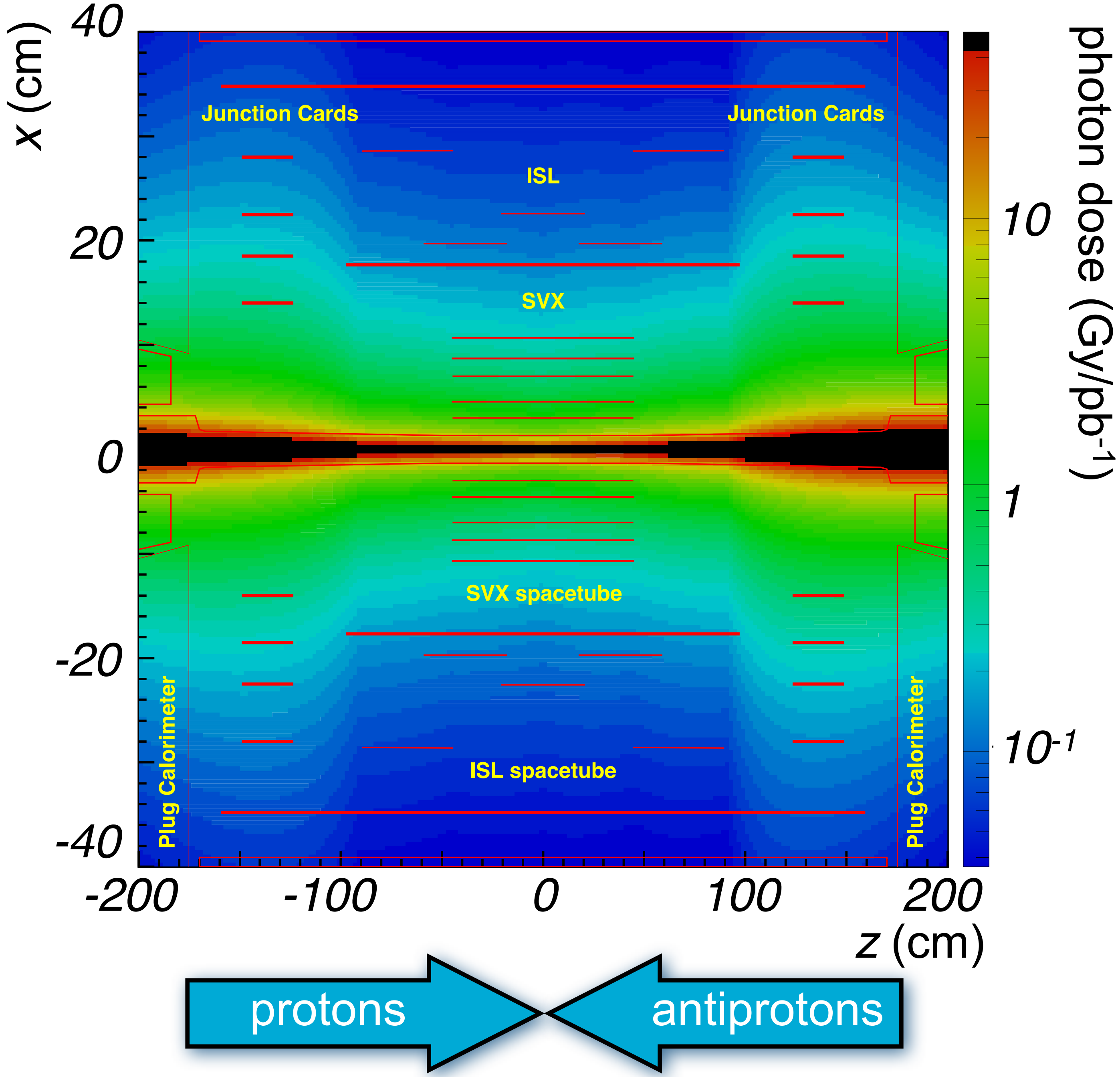




Hard to get more than just "evidence" for beam-related operational problems

CDF Radiation Monitoring

Radiation field from $p\bar{p}$ collisions



[R. J. Tesarek *et al.*, IEEE NSS 2003]

- Radiation field measured by >1000 thermo-luminescent dosimeters (TLDs) in tracking volume
- Accurate radiation map
- *z*-dependent radial scaling: dose proportional to $r^{-\delta}$ with $1.5 < \delta < 2.1$
- Dose dominated by collisions (> 90%), remainder from beam losses

Using CDF SVX II as a Dosimeter

- Linear increase of bulk leakage current I_{leak} with fluence Φ:

  $$\Delta I_{leak} = \alpha\Phi$$

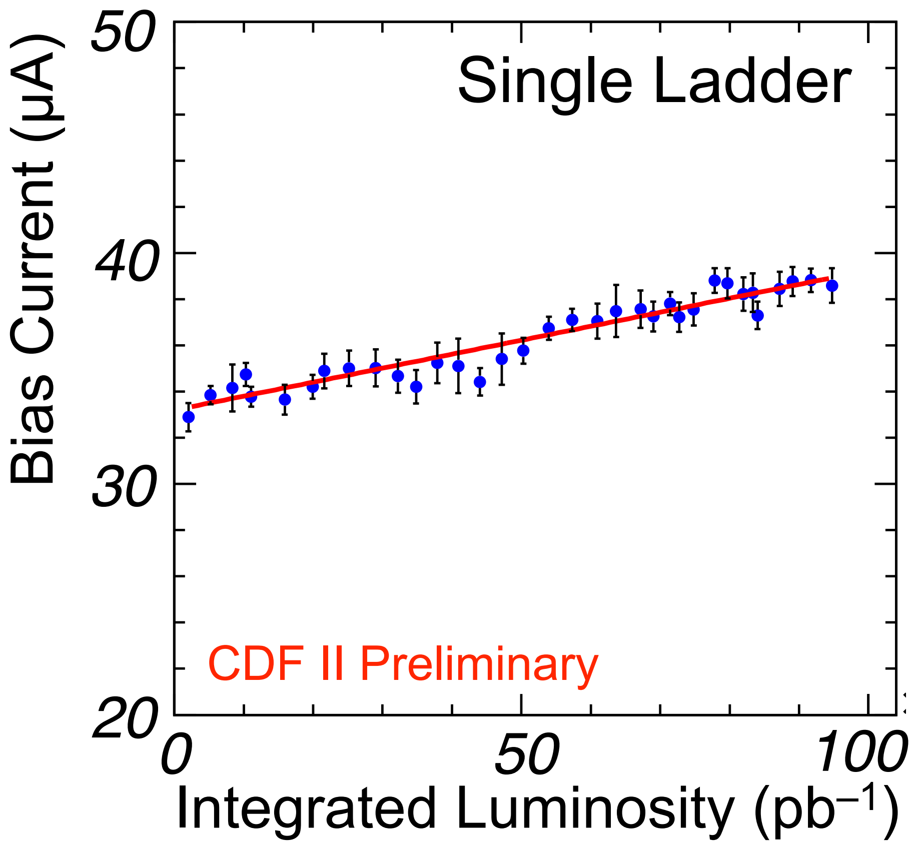
  with α "damage parameter"

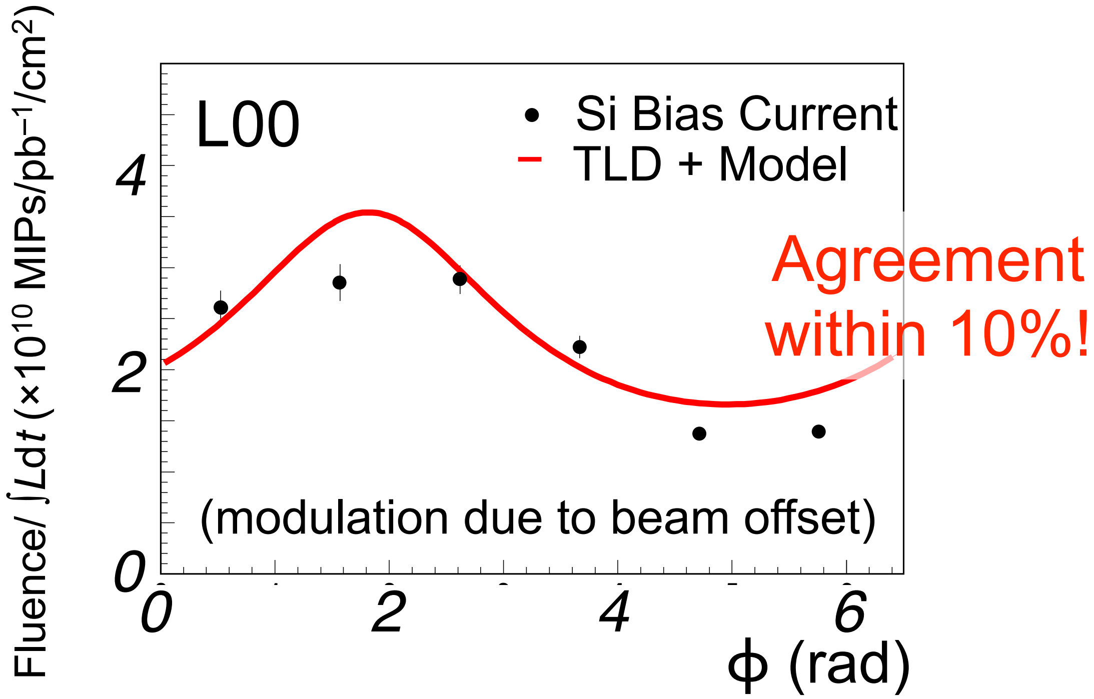
- Assume: change in observed bias current dominated by change in leakage current

  $$\Delta I_{bias} \approx \Delta I_{leak}$$

- Note: leakage currents strongly temperature-dependent, typically normalized to 20ºC

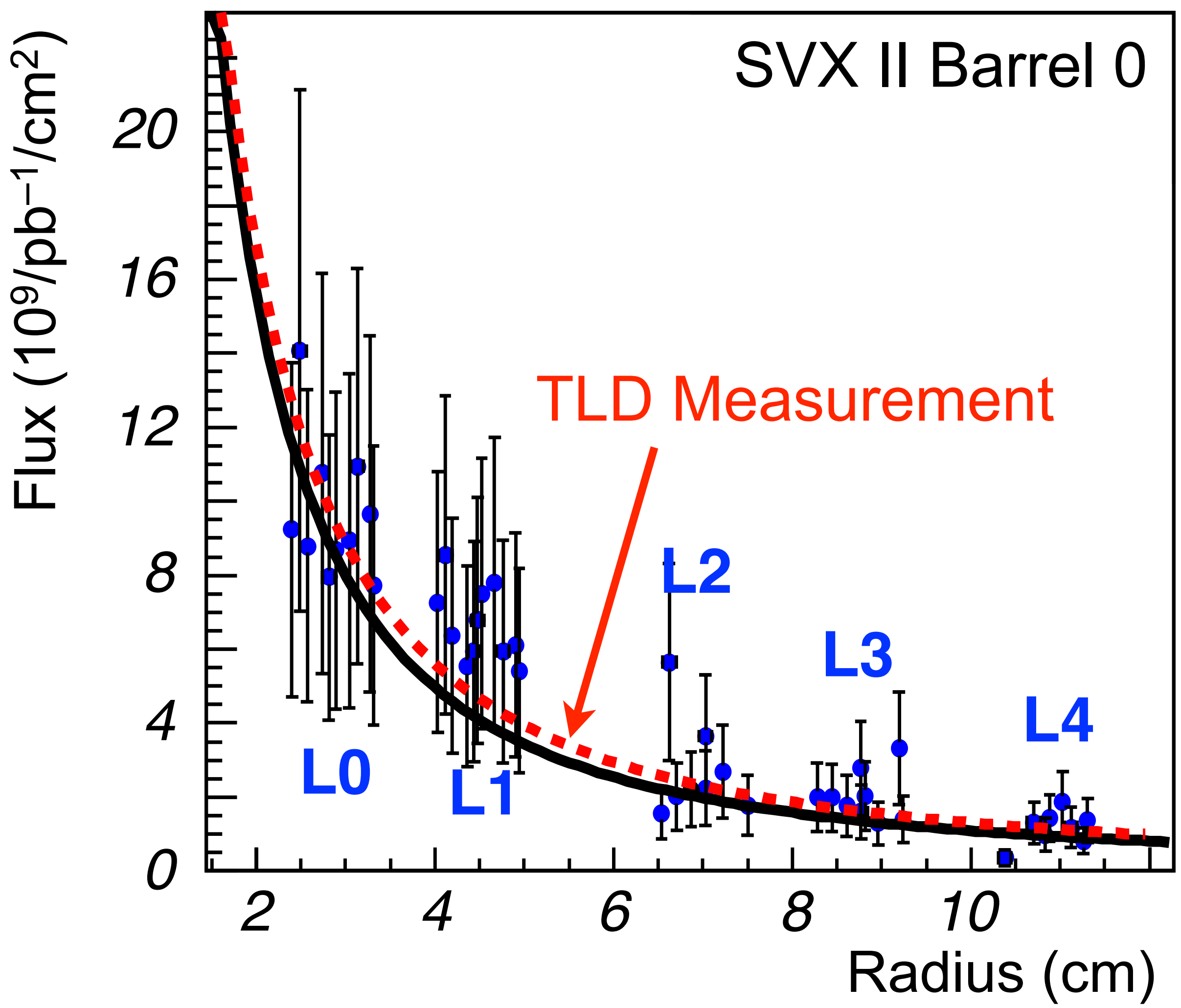
> Impossible to measure theoretical quantities like "leakage current" directly in real experiment, there's always the rest of the detector "in the way"





[R. J. Tesarek *et al.*, IEEE NSS 2003]

Using CDF SVX II as a Dosimeter



1. Fix normalization: measure effective damage parameter by comparing with TLD measurements:

$$\alpha_{\text{eff}}^{\text{CDF}} = (4.39 \pm 0.02) \times 10^{-17}\,\text{A/cm}$$

2. Extract flux as a function of radius, e.g. for SVX II Layer 0

$$\frac{\Phi_{\text{L0}}}{\int \mathcal{L}dt} = (0.93 \pm 0.26) \times 10^{13}\,\frac{1\,\text{MeV}\,n}{\text{cm}^2\,\text{fb}^{-1}}$$

(estimated from measured dose assuming NIEL scaling)

- Large uncertainties:
  - Temperature model: 13%
  - Extraction of α: 20%

Difficult to compare thermal behavior in detector environment with laboratory measurements (e.g. annealing: 80 minutes at 60ºC)

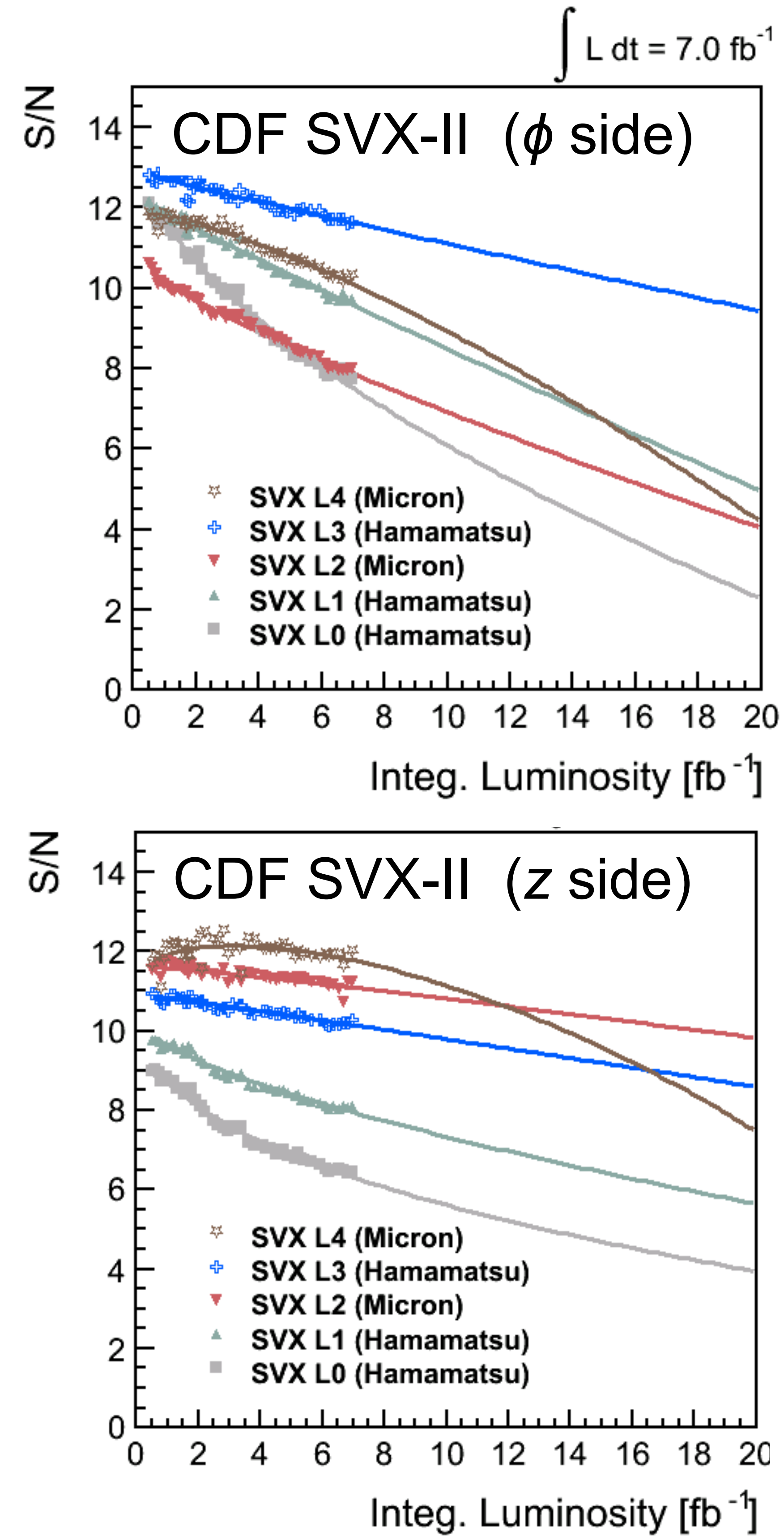
Monitoring of Radiation Damage

- Signal-to-noise ratio: any signs of abnormal efficiency loss?
  - Signal: cluster charge from from J/ψ → μμ (corrected for path length of track in silicon)
  - Noise: regular calibration runs
  - Extrapolation (assuming full depletion)

$$S/N = \frac{ax + b}{c\sqrt{x} + d}$$

signal: charge collection efficiency reduction ~ Φ
noise: leakage current increase ~ √Φ

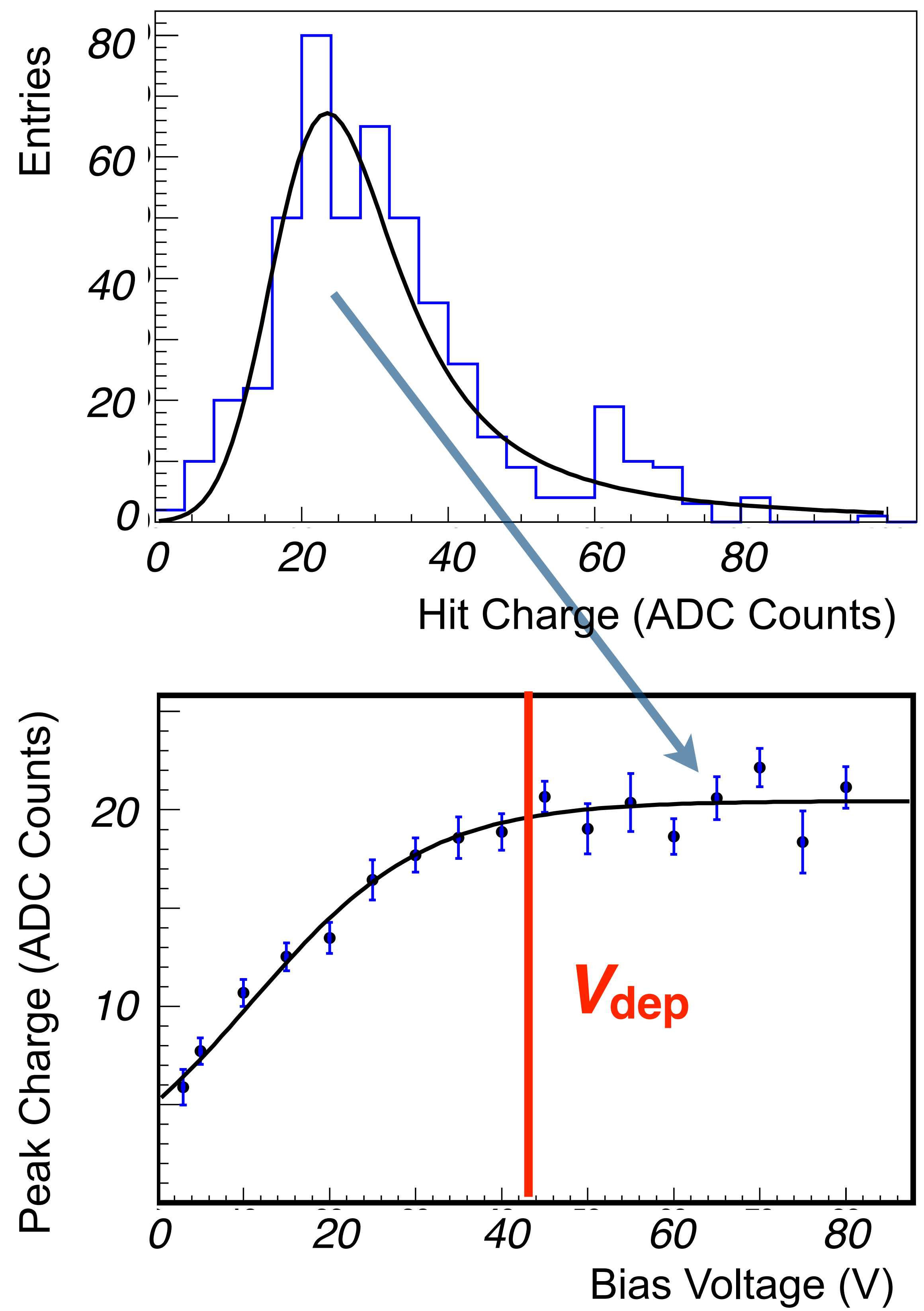
- Regular monitoring of operational parameters
  - Leakage current: bias current measurement (usually included in slow control)
  - Depletion voltage from signal vs. bias scans: Expected behavior (type inversion, …)? Signs of efficiency loss through under-depletion?



Depletion Voltage: Signal vs. Bias

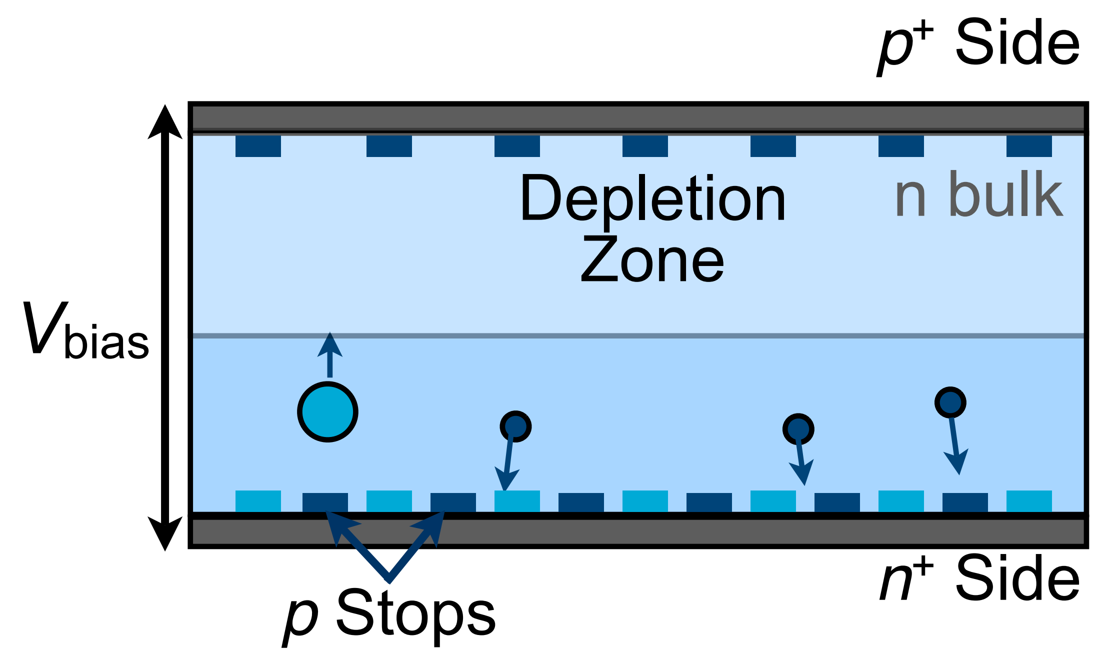
- Dedicated data-taking runs ("Signal Bias Scans")
  - Study collected charge of silicon hits from good tracks during colliding beams operation
  - Find peak of ADC spectrum as a function of bias voltage (fit: Landau ⊗ Gaussian)
  - Determine V_{dep} e.g. as 95% amplitude of sigmoid fit
- Works for entire detector, but consumes valuable beam time

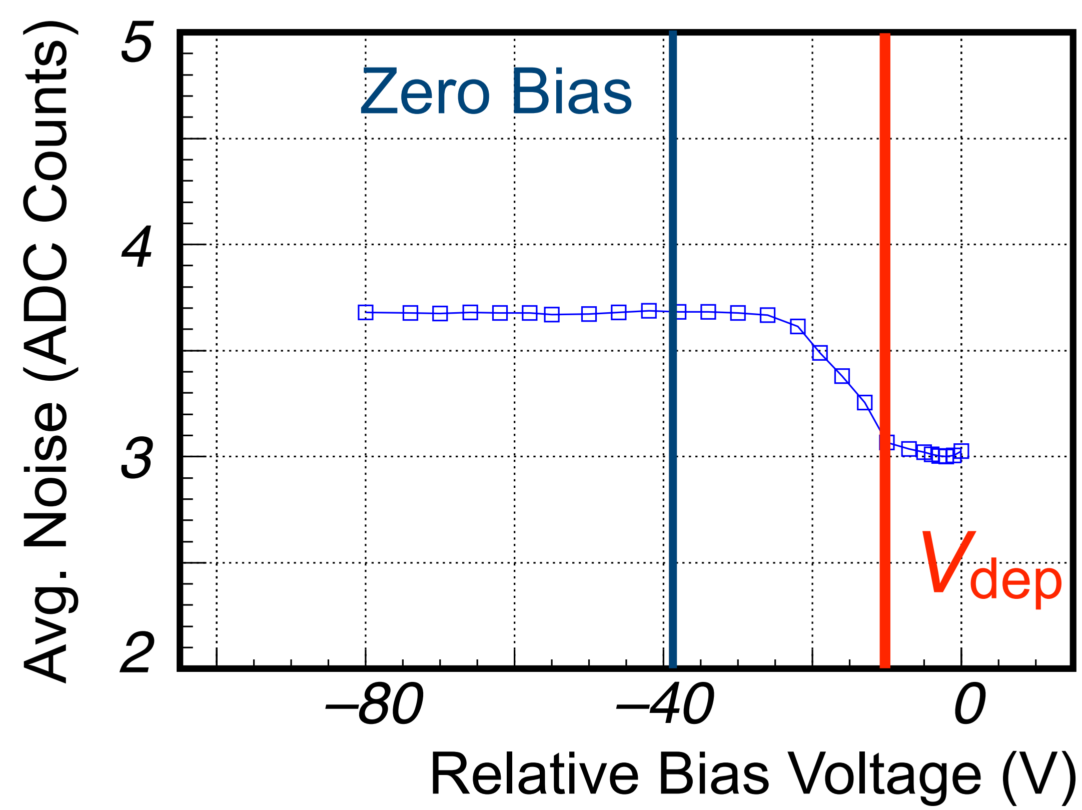
Cannot measure depletion voltages via C–V curves in a running experiment, also results may not be 100% compatible



Depletion Voltage: Noise vs. Bias

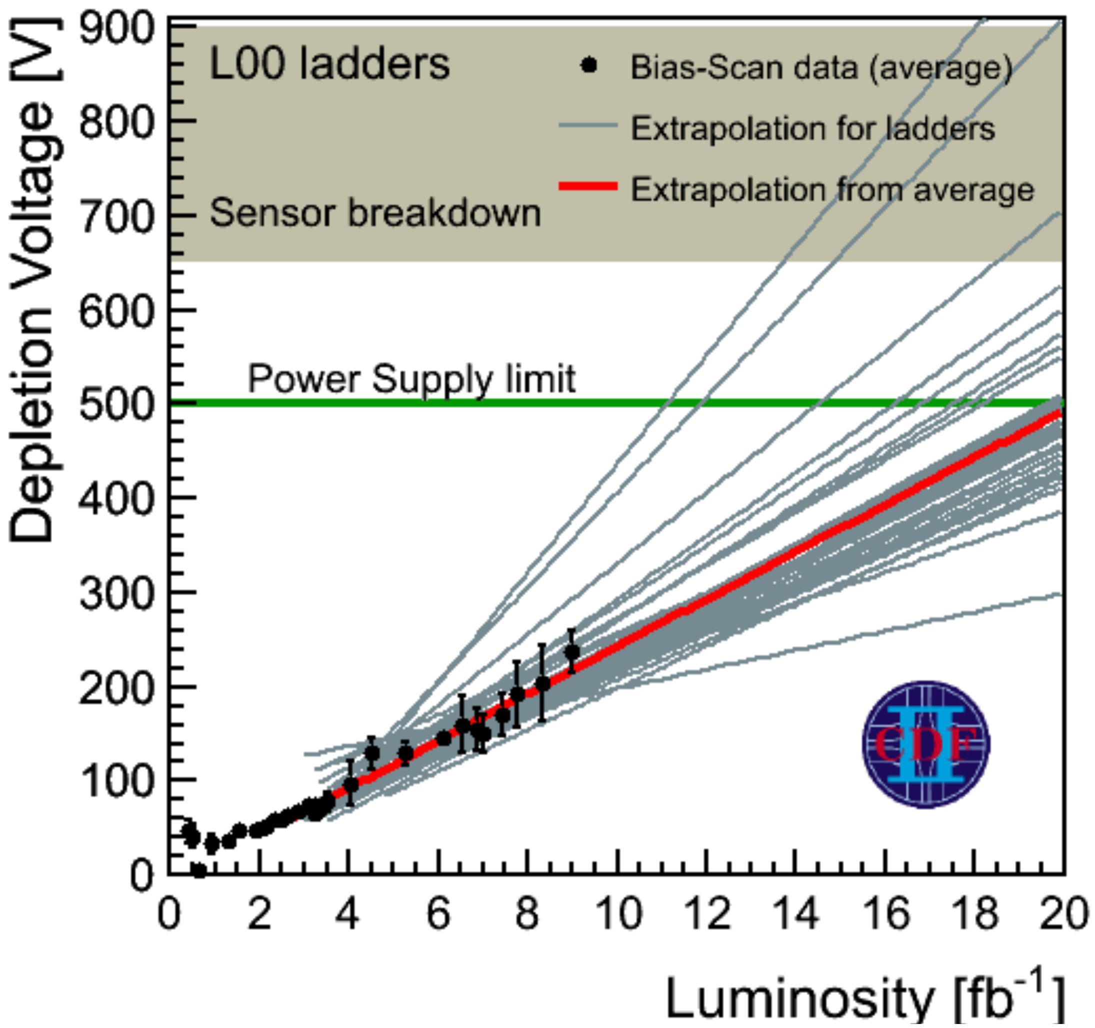
- “Noise Bias Scans”: study average noise as a function of bias voltage
- Measurement idea: inter-strip thermal noise on *n* side cleared by applying bias voltage → fully depleted detector has lower noise level
- Works only for double-sided sensors (e.g. CDF SVX II)
- Advantage: does not require beam in accelerator → no interference with data-taking
- Method does not work after after type inversion (no *p* stops on p^+ side)

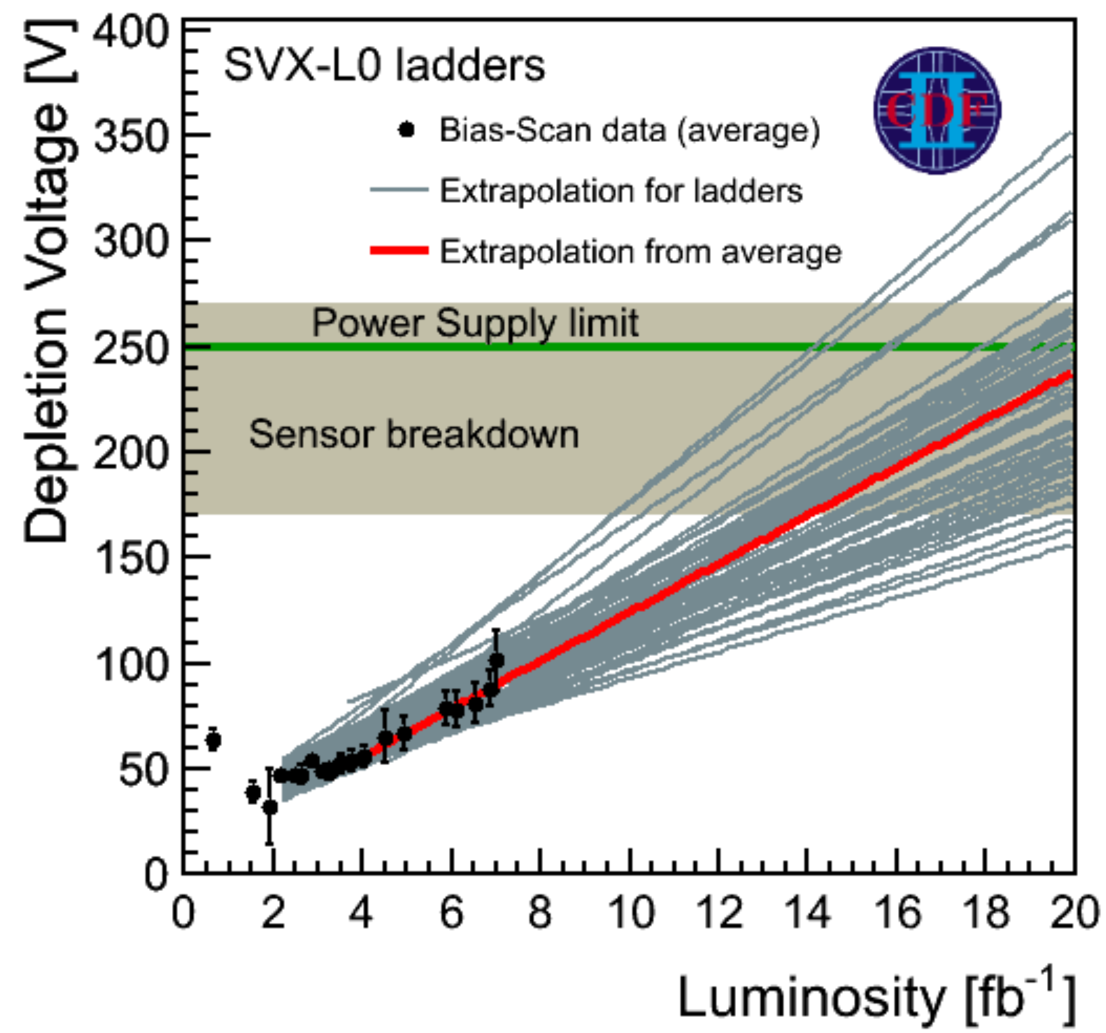




Latest CDF Bias Scan Results

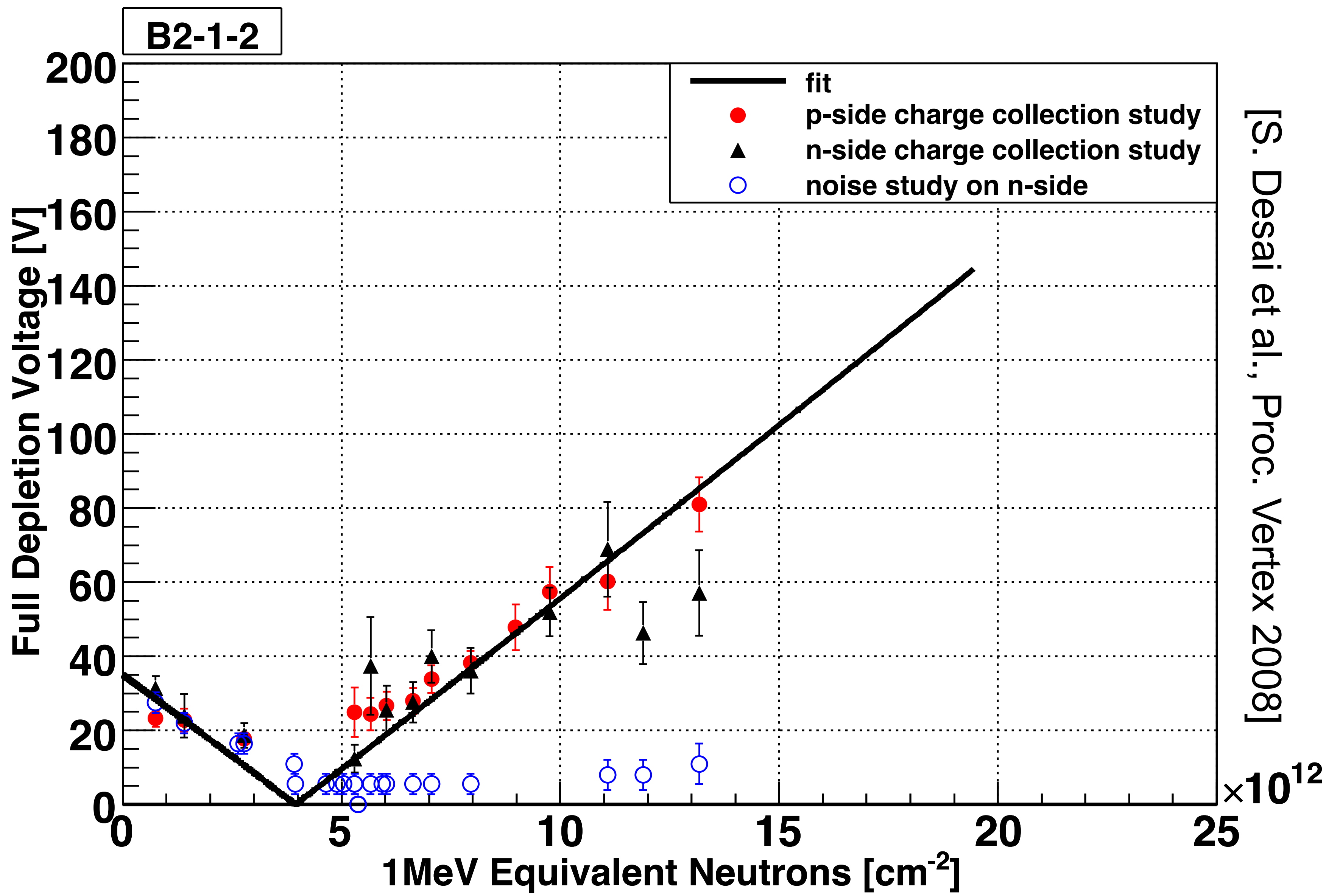
- Depletion voltage evolution for innermost layers: L00 and SVX II Layer 0
  - Straight-line fit to extrapolate to higher luminosities (Run III): average and individual ladders → fairly consistent behavior
  - As expected: innermost SVX II layer gets inefficient first, L00 will survive





[O. Gonzalez, R. Ballarin, A. DiCanto]

DØ Depletion Voltage Results 2008



[S. Desai et al., Proc. Vertex 2008]

- DØ methodology very similar to CDF: signal-bias and noise-bias scans (which stopped working after type inversion)
- New: conversion to equivalent fluence, fit to Hamburg model (radial dependence of radiation field floating in fit)

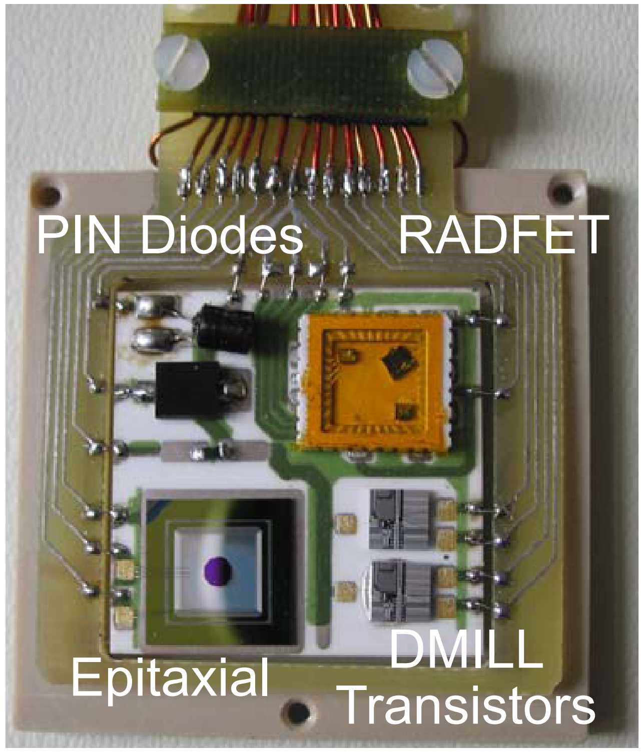
Mitigation of Radiation Damage

- Benefits of operating at lower temperatures
  - Lower leakage currents → less noise
  - Reduction of reverse annealing effects → longer lifetimes
- Limitations
  - Technical imitations: minimum temperature of chiller system, coolant, piping, …
  - Challenge to keep detector cold at all times: maintain full cooling even during power outages & long shutdown periods
- LHC: coolant at –25ºC
  - Sensor temperatures around –10ºC
  - High-lumi upgrade: CO_2-based cooling systems favored → –35ºC

Cooling System Repair at CDF (2007)

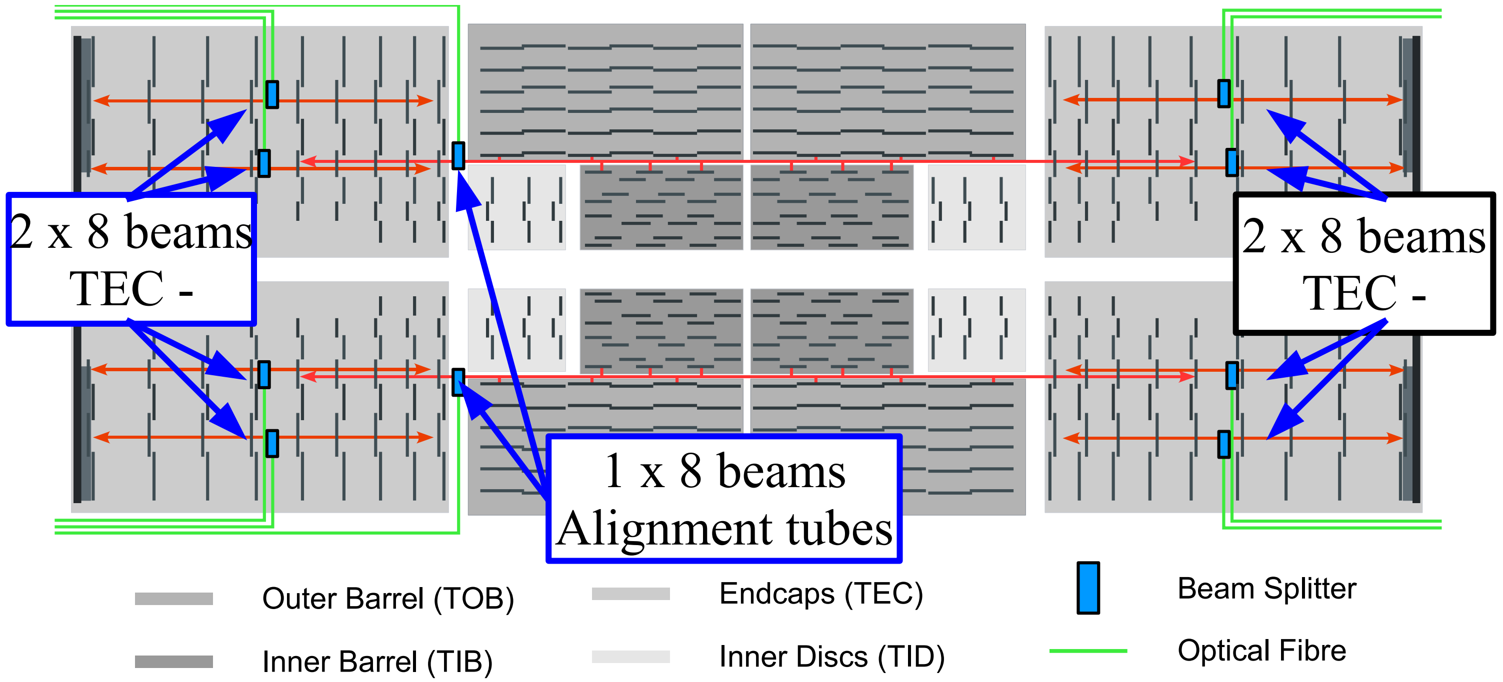
Radiation Monitoring at the LHC

- ATLAS: deployed 14 small detector modules in inner detector
  - Ionizing dose: RADFETs
  - Equivalent fluence Φ_{eq}: PIN diodes and pad diode made of epitaxial silicon
  - Thermal n: radiation-hardened transitors



[I. Mandic]

- CMS: Measurements of depletion voltage with signal-bias scans and noise-bias scans
- CMS: ideas to use tracker laser alignment system
  - Measure charge produced by well-defined laser pulse as a function of bias voltage
  - Pro: no beam time consumed
  - Con: tests only few modules



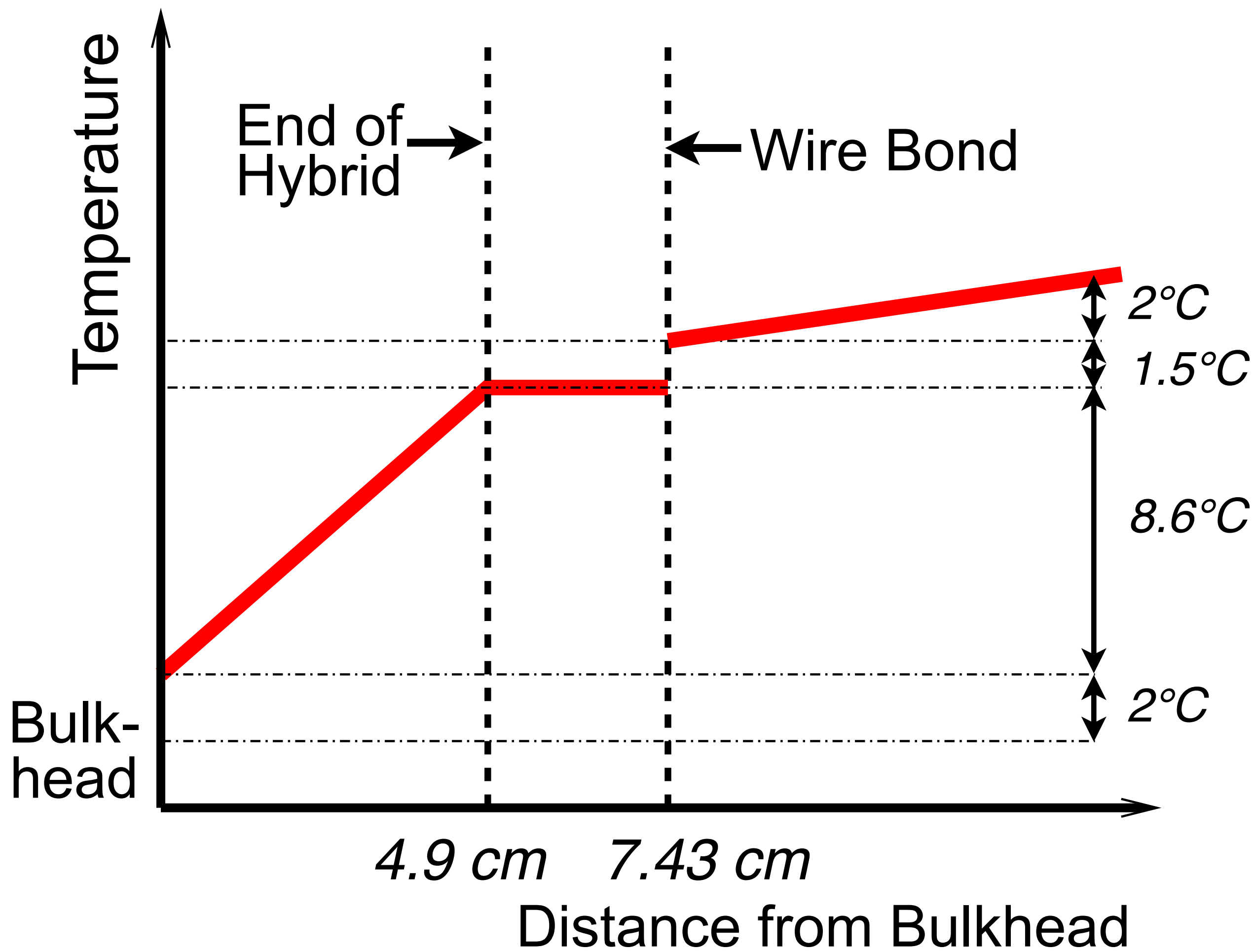
[B. Wittmer, Vertex 2009]

Summary & Conclusions

- Radiation hardness: critical for any tracking detector at a hadron colliders
- Lots of progress on the level of R&D (e.g. RD50), but findings must be applied to real-life detectors
  - Technologies typically frozen 5–10 years before start of operation
  - In-situ measurements more difficult than laboratory measurements: accessibility, instrumentation, thermal behavior, …
- Hadron collider experiments:
  - Careful monitoring of radiation damage → in-situ results are consistent with laboratory measurements
  - Mitigation of radiation damage through operational measures
  - Interesting results coming up from the LHC

Backup Slides

CDF SVX II Temperature Model



$$\frac{I_2}{I_1} = \left(\frac{T_2}{T_1}\right)^2 \exp\left[\frac{E_{gap}}{2k_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

- Convention: normalize bias currents to 20°C
- SVX II: temperature sensors (RTDs) mounted on support structure ("bulkhead"): no direct measurement on silicon sensor, need extrapolation
- Temperature extrapolation relies on early finite element analysis for sensor temperature → large systematic uncertainties of temperature correction factor (13%)

Difficult to compare thermal behavior in detector environment with laboratory measurements (e.g. annealing 80 minutes at 60ºC)