# Radiation simulations in detector design

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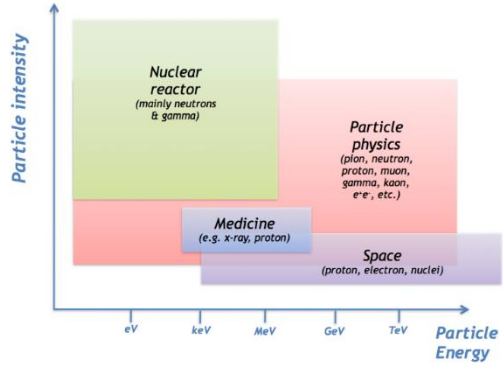
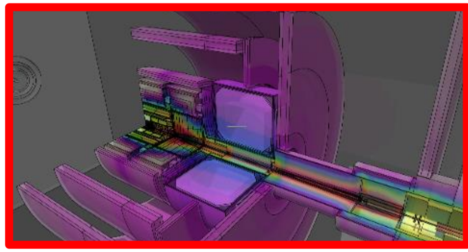
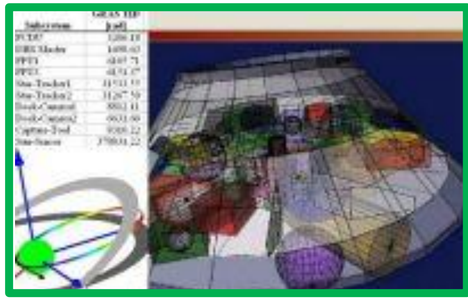
# Introduction

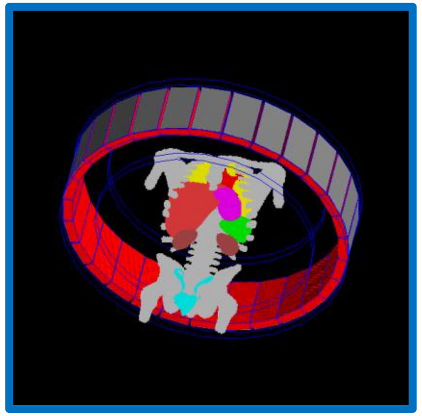
# Simulations of radiation environments

- Long-term immersion in radiation environments can lead to several issues for detector systems
  - Single event effects (e.g., noise occupancy in sensors, bit flips in electronics) can affect integrity of data
  - Radiation damage to sensors and electronics can cause long-term degradation in performance or even complete failure
  - Structural elements can be weakened by prolonged radiation exposure
  - Radioactivation of detector components can affect maintenance procedures
- Simulations of radiation environments can provide an important input in the design of detectors
  - Simulations can be used to mitigate against the effects of radiation damage in sensor components
  - Supplement irradiation tests of detectors + components
- GEANT4 and FLUKA are Monte Carlo software toolkits used for radiation simulations
  - Each simulates the passage of particles through matter
  - Wide range in areas of application, including high energy physics, space science and medical science







# Monte Carlo simulations

- Create a model of geometry and material for the full sensor environment, **including any surrounding material** such as shielding or mounting jigs
  - Material outside the physics acceptance can have a strong influence on the radiation environment through back scattering
  - Important to have **correct mass and material composition** of each sensor component
  - Trace elements important for radioactivation simulations
- Create a model of the irradiation source
  - Specify type of particles, energy spectrum, geometrical distribution
- Monte Carlo package simulates the transport of the irradiation particles, including any interactions in sensor + surrounding material
  - Many irradiation events are simulated
  - **Results are typically averaged over all events** to produce average response

# Radiation Resilient Ultrasonic Sensors project

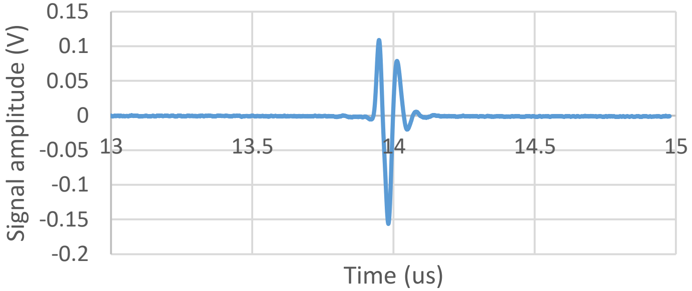
# RRUS project

- Nuclear industry uses ultrasonic testing techniques for non-destructive inspection of safety-critical components in reactors + waste storage units
  - E.g., 1 MGy can correspond to 3 months monitoring of high-level nuclear waste
  - Commercial sensors have limited radiation endurance
- Innovate UK funded two projects to develop **radiation resilient ultrasonic sensors** robust enough for prolonged use in high-radiation environments
  - **RRUS**: post-operation inspections (mainly gammas)
  - ReDRESS: in-operation monitoring of nuclear reactors (gammas + neutrons)
- The University of Sheffield was responsible for developing a GEANT4 simulation of the sensors + radiation environments
  - Commercial partners (Precision Acoustics, TWI, Ionix) designed + tested prototype sensors

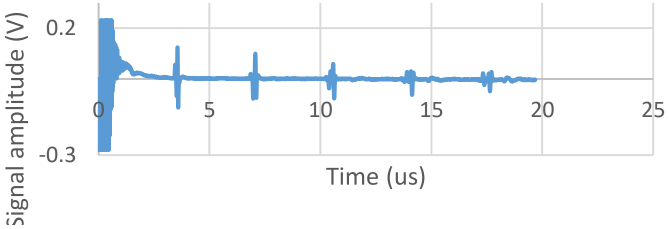
# Ultrasonic transducers

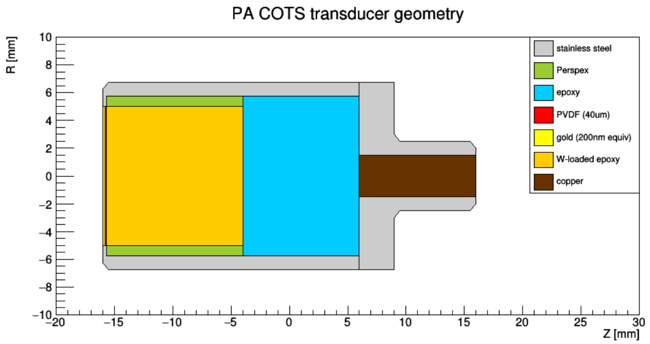
- High imaging resolution required to monitor, e.g., formation + growth of cracks in components
  - Ultrasonic transducers need to achieve MHz frequencies
- Piezopolymer PVDF (polyvinylidene fluoride) is ideal for high frequency + high bandwidth applications
  - Irradiation of PVDF leads to chain scission, and subsequently cross-linking of polymer chains
  - Results in physical embrittlement of PVDF
  - Difficult to improve innate radiation resilience of PVDF
- COTS (Conventional Off-The-Shelf) transducers typically use epoxy resin as an adhesive agent
  - Gamma irradiation of epoxy leads to formation of gasses
  - Extended radiation exposure can cause build-up of gas pressure, stresses within the material

PVDF transducer, typical pulse-echo response



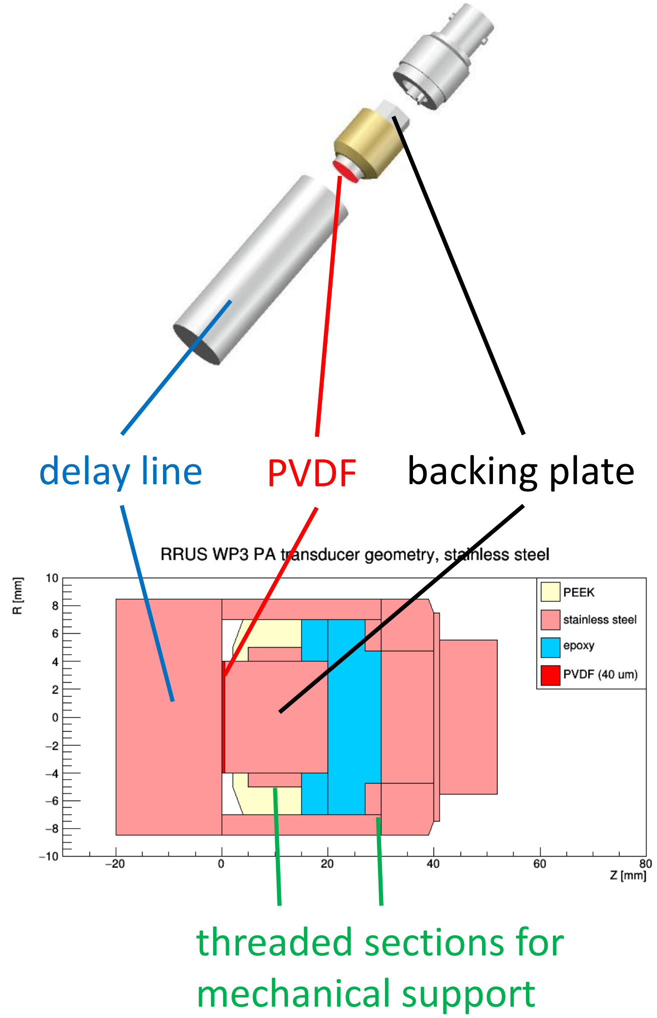

Acquisition from 10mm delay line transducer




# RRUS transducer design

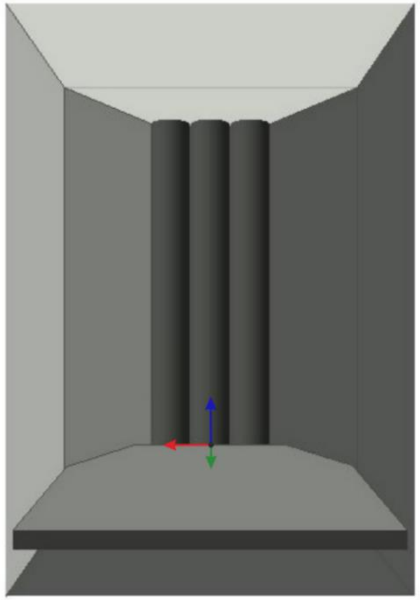
- Precision Acoustics designed + fabricated transducers with stainless-steel housing
  - Also trialled tungsten alloy housing
- 20-mm acoustic delay line acts as radiation shield for the PVDF film
- All components designed to screw together mechanically via threaded sections
  - Assembled with torque wrench to counter pressures from radiolytic gas production in epoxy
  - No reliance on adhesive bonds

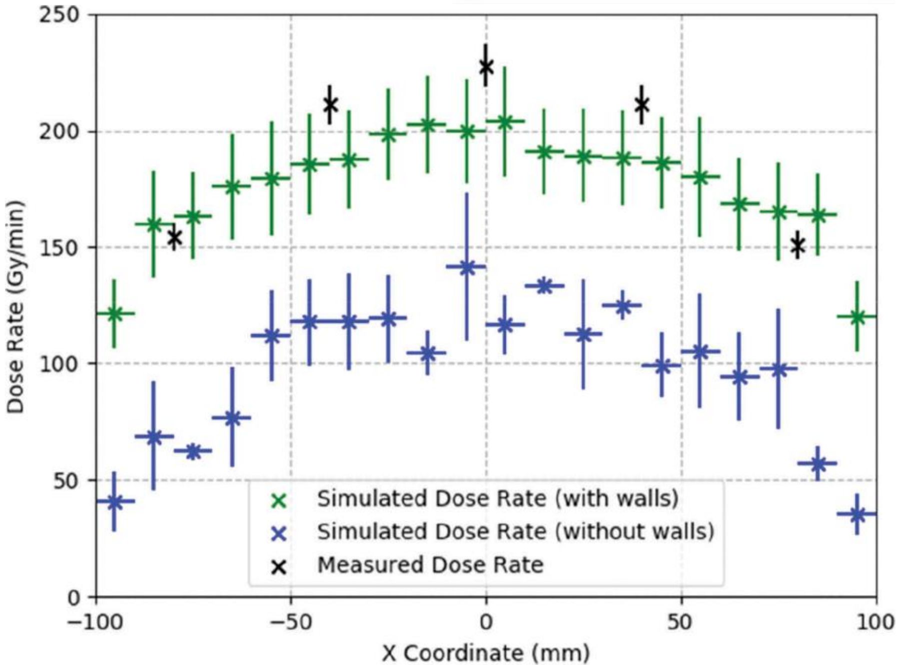


# DCF Co-60 irradiator simulation



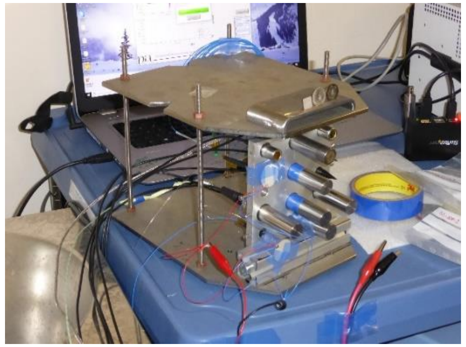
- Prototype probes were irradiated for 14 days during August 2018 with Cobalt-60 source at The University of Manchester's Dalton Cumbrian Facility (DCF)
  - Co-60 emits mainly gamma rays with energies 1.17 & 1.33 MeV
- Developed simulation of Co-60 irradiation chamber
  - Important to understand radiation environment inside chamber + dose profiles within devices under test
- Simulation predictions were benchmarked with **dose rate measurements** taken in empty chamber
  - Generally good agreement; variation typically less than 30%
  - Gives confidence in simulation predictions for probe irradiation test
- Importance of including steel chamber walls in simulation shown by previous version without walls
  - Back scattering from walls increases dose rates

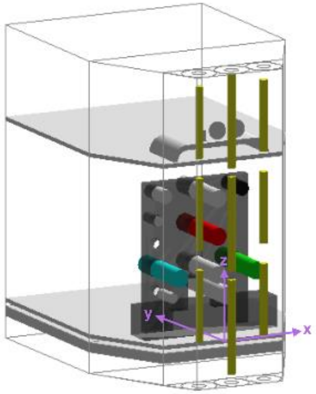




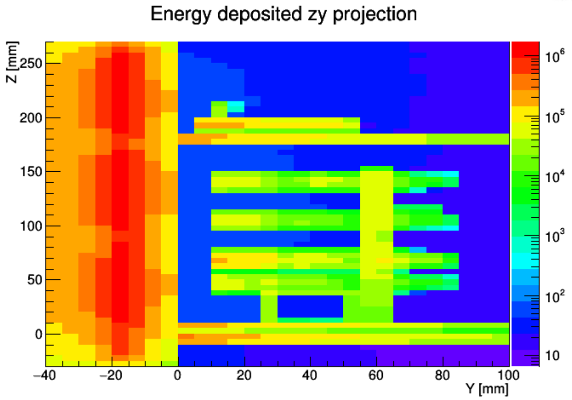
# RRUS irradiation at DCF

- Simulated the test setup used in DCF irradiation
  - Highlighted three prototype probes (PVDF thicknesses 52um, 40um, 110um) + **COTS** probe
  - Nine Cobalt-60 rods also visible

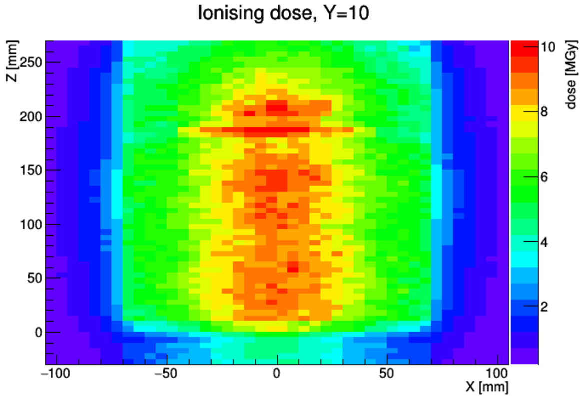




- Side projection of energy deposited
  - Probes and test stand clearly visible



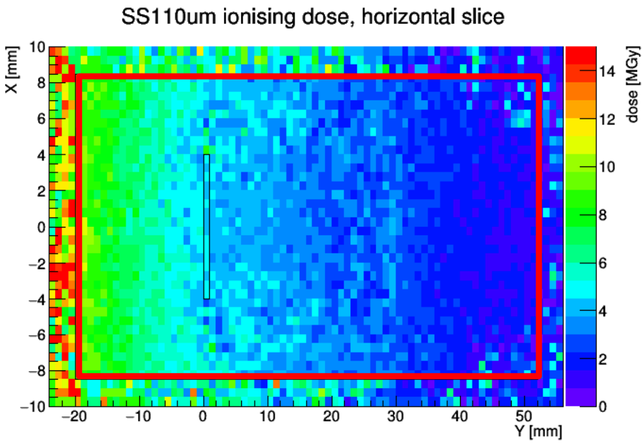

- Front view of dose at front face of probes
  - Dose highest along central axis of chamber
  - Decreases towards sides of chamber

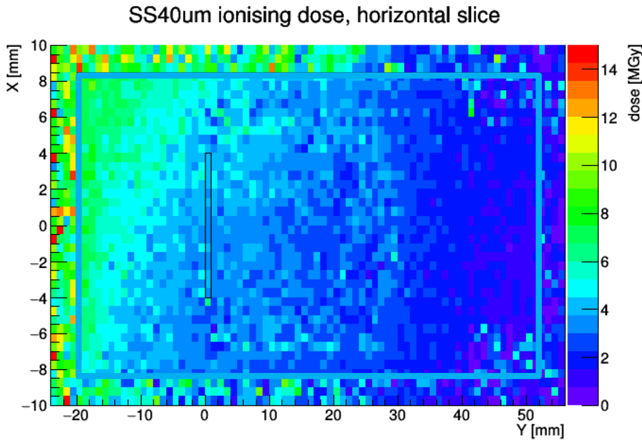


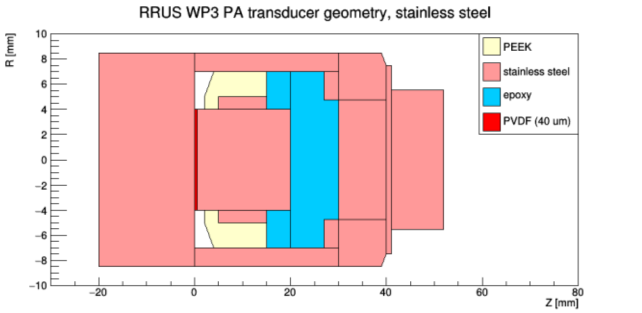
# Dose profiles in probes

- For probe located along central axis (SS110um), no horizontal asymmetry in dose profile
- For probe located off central axis (SS40um), clear horizontal asymmetry in dose profile
  - Dose higher towards centre of chamber
- Dose values at front face of probe and at PVDF obtained from dose profiles
  - Dose at PVDF reduced due to shielding effect of delay line

| Probe | Dose at front [MGy] | Dose at PVDF [MGy] | Ratio PVDF/front |
|---|---|---|---|
| SS52um | 7.27 | 3.87 | 0.53 |
| SS40um | 7.15 | 3.83 | 0.54 |
| SS110um | 10.46 | 4.47 | 0.43 |

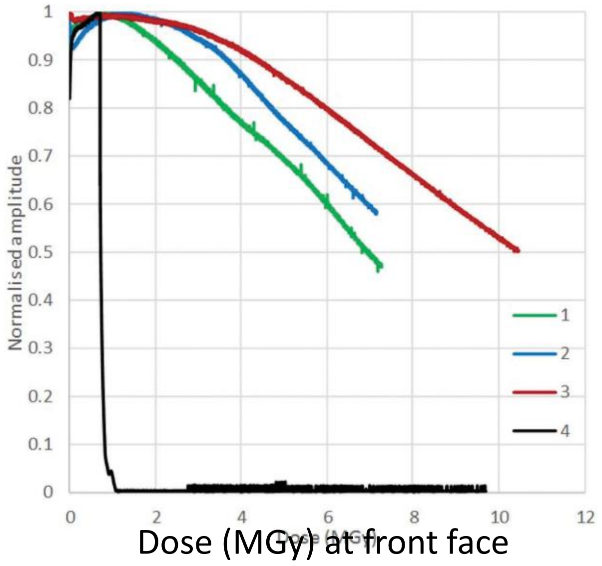


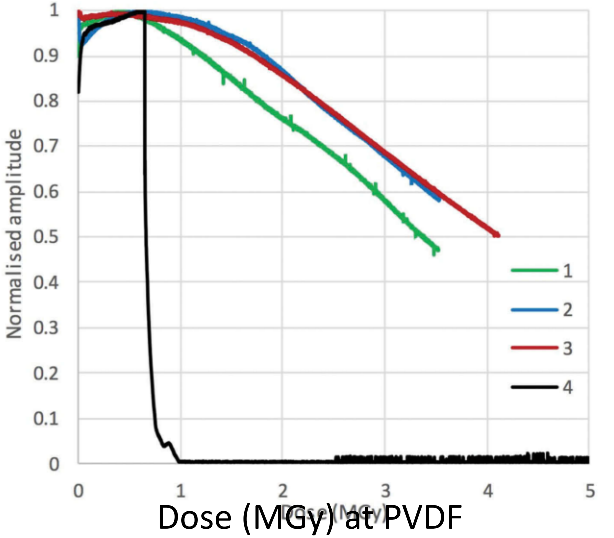



# Irradiation results

- Probes were irradiated up to maximum cumulative gamma dose of 10.5 MGy; corresponds to 4 MGy at PVDF
  - Previous literature up to 1 MGy
- New shielded probe designs more resilient to radiation than COTS design
  - COTS PVDF delaminated from backing material, showed high levels of embrittlement
  - New designs showed no signs of severe degradation
- Probe performance improved up to ~500 kGy
  - Radiation-induced chain scission increases dipole moment of PVDF
  - Beyond 500 kGy, increased crosslinking leads to stiffening of PVDF
- Results published in Nondestructive Testing and Evaluation, Volume 35, Issue 2
  - [In situ monitoring of PVDF ultrasound transducers under gamma irradiation]

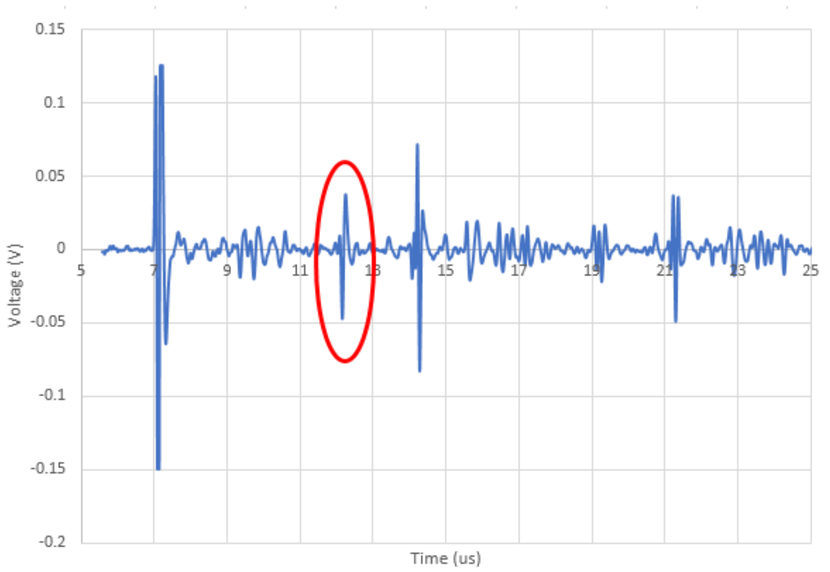


# Post-irradiation probe operation



- Irradiated probe was used to scan steel test block with a FBH (flat bottom hole) defect at 15mm depth
  - Defect is clearly visible in scan
  - Demonstrates that probes remain functional post-irradiation

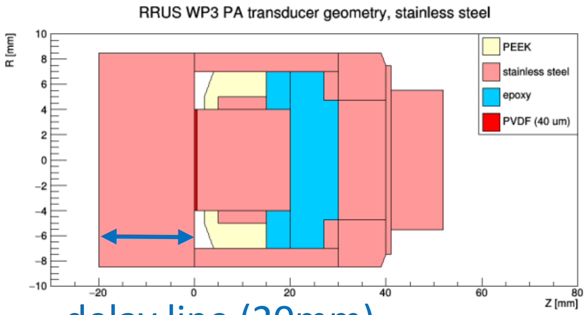


# Shielding design study

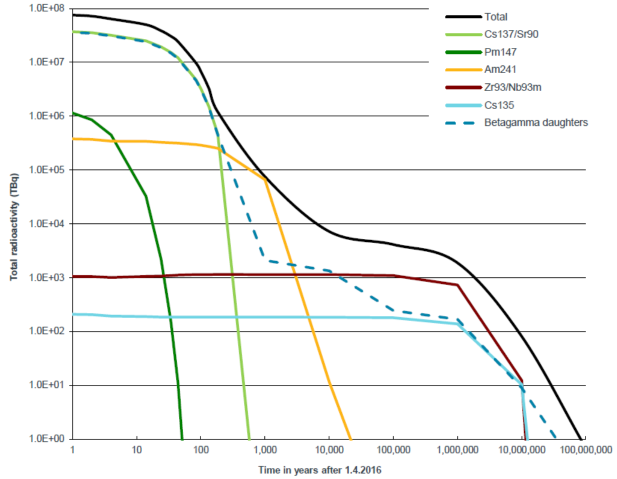


- Studied impact of varying the length of stainless steel delay line
  - Simulated large planar source of cesium-137 and strontium-90 in front of delay line
  - Cs-137 and Sr-90 (+ daughters) are dominant isotopes in high-level waste (NDA 2016 waste inventory)
- Compared with dose ratio calculated from attenuation coefficient for steel (0.426 $cm^{-1}$); corresponds to radiation entering solely through the front face
  - As delay line length increases, ratio from simulation decreases more slowly than ratio from attenuation calculation
  - Radiation entering from side of probe increasingly significant relative to radiation entering from front

| Shielding length [mm] | Ratio PVDF/front from simulation | Ratio PVDF/front from attenuation calculation |
|---|---|---|
| 10 | 0.63 | 0.65 |
| 20 (baseline) | 0.49 | 0.43 |
| 30 | 0.36 | 0.28 |
| 40 | 0.29 | 0.18 |

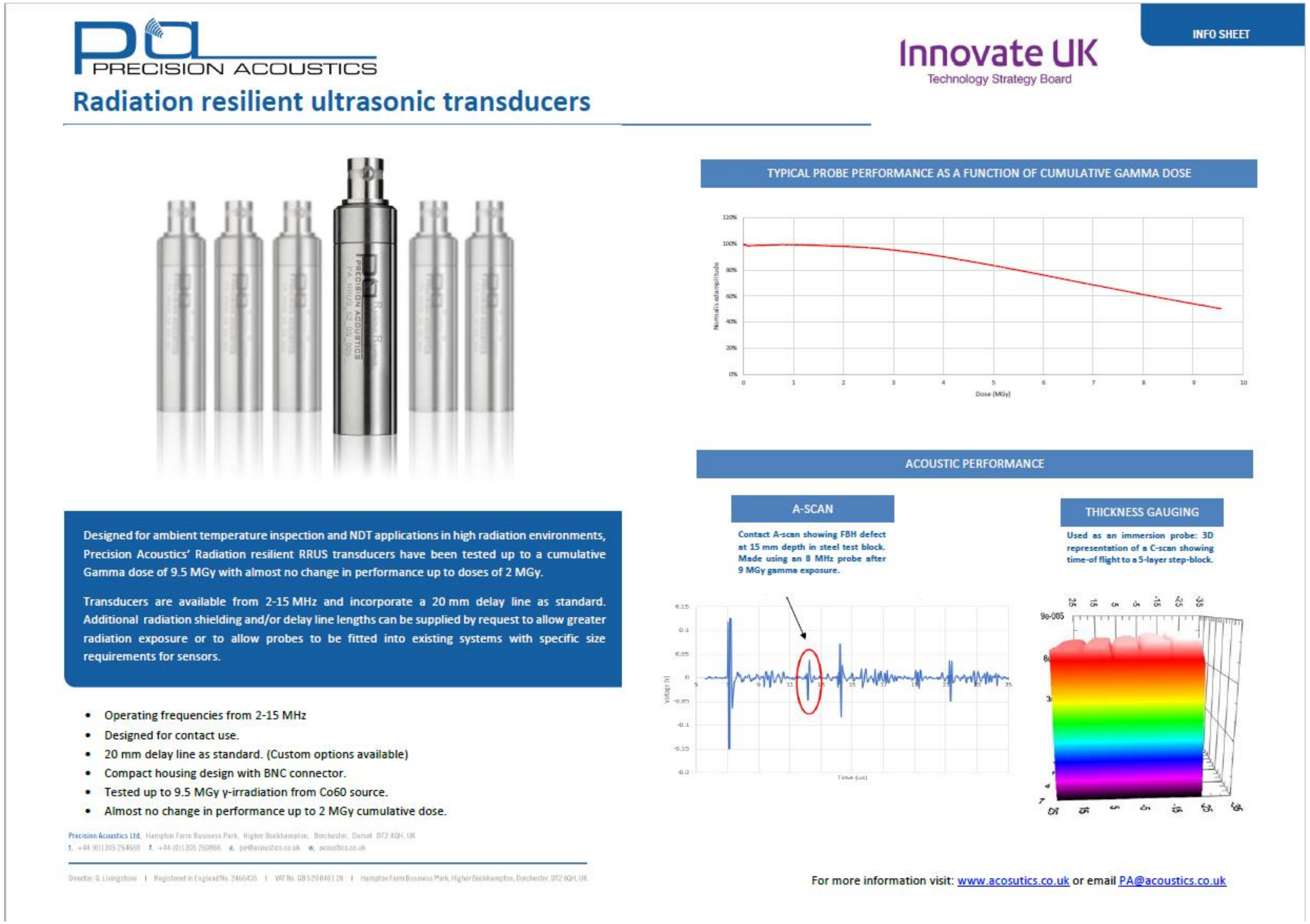



delay line (20mm)



# RRUS commercialisation

- Based on success of RRUS project, Precision Acoustics are marketing radiation resilient ultrasonic transducers



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## Radiation resilient ultrasonic transducers

TYPICAL PROBE PERFORMANCE AS A FUNCTION OF CUMULATIVE GAMMA DOSE

Designed for ambient temperature inspection and NDT applications in high radiation environments, Precision Acoustics' Radiation resilient RRUS transducers have been tested up to a cumulative Gamma dose of 9.5 MGy with almost no change in performance up to doses of 2 MGy.

Transducers are available from 2-15 MHz and incorporate a 20 mm delay line as standard. Additional radiation shielding and/or delay line lengths can be supplied by request to allow greater radiation exposure or to allow probes to be fitted into existing systems with specific size requirements for sensors.

ACOUSTIC PERFORMANCE

A-SCAN

Contact A-scan showing FBH defect at 15 mm depth in steel test block. Made using an 8 MHz probe after 9 MGy gamma exposure.

THICKNESS GAUGING

Used as an immersion probe: 3D representation of a C-scan showing time-of flight to a 5-layer step-block.

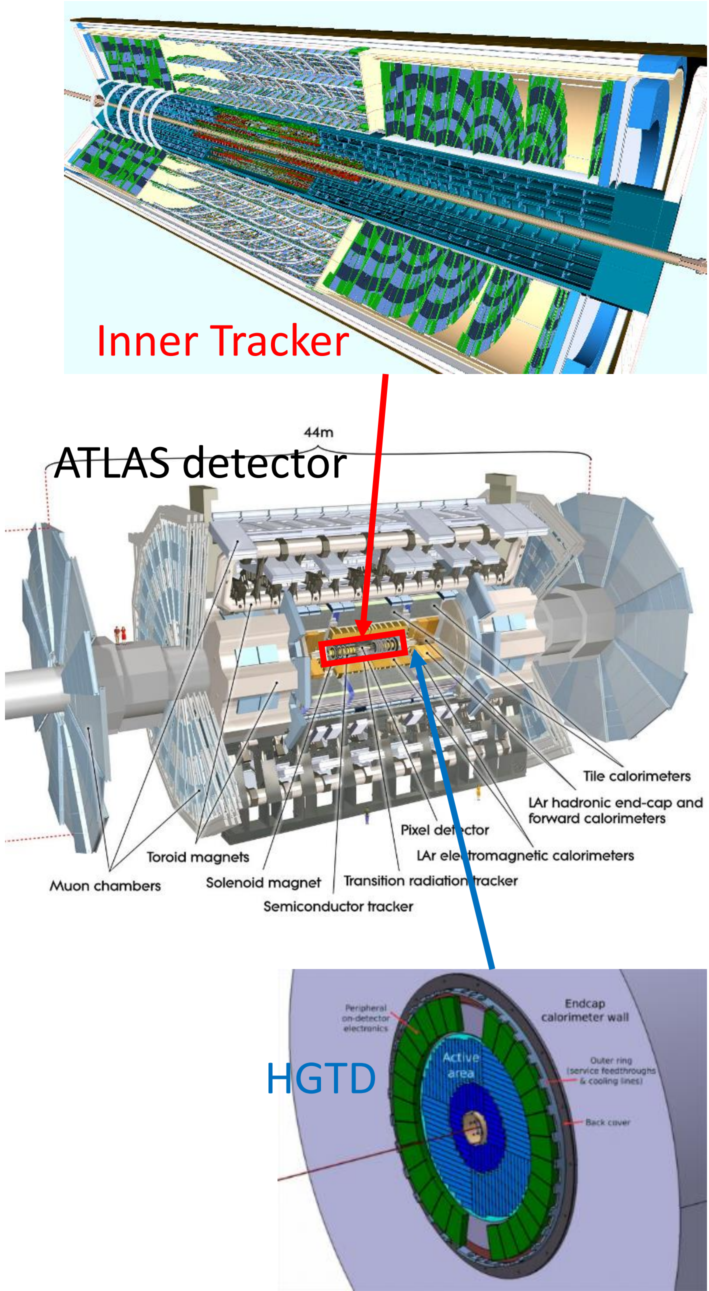
- Operating frequencies from 2-15 MHz
- Designed for contact use.
- 20 mm delay line as standard. (Custom options available)
- Compact housing design with BNC connector.
- Tested up to 9.5 MGy γ-irradiation from Co60 source.
- Almost no change in performance up to 2 MGy cumulative dose.

For more information visit: www.acosutics.co.uk or email PA@acoustics.co.uk

# ATLAS Upgrade project

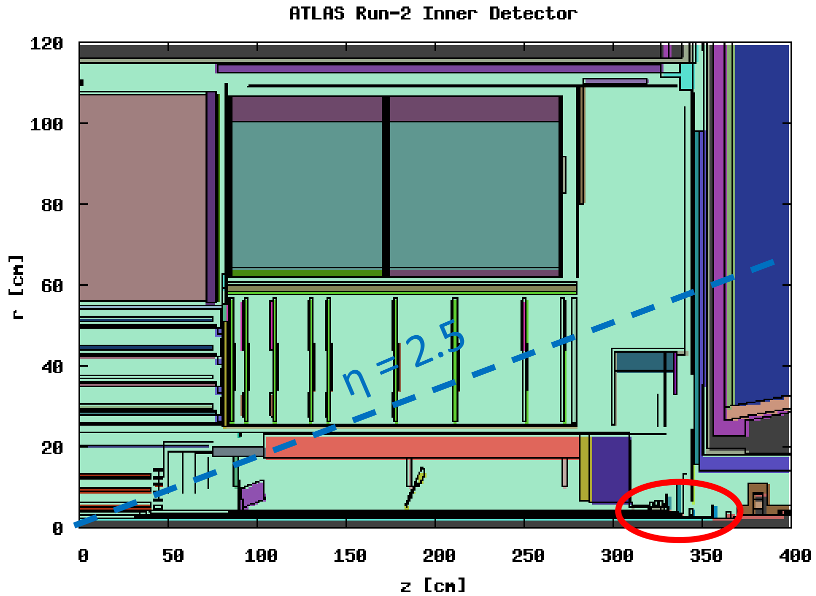
# ATLAS Upgrade project

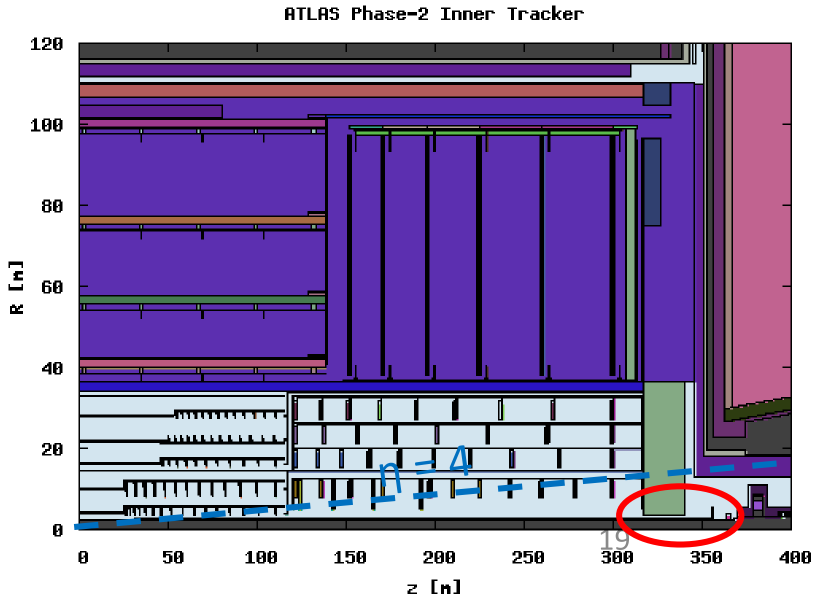
- Starting in 2025, the LHC will be upgraded to the High-Luminosity Large Hadron Collider (HL-LHC)
  - HL-LHC will deliver a fivefold increase in instantaneous luminosity, tenfold increase in integrated luminosity
- At the same time, ATLAS will install a number of Phase-II Upgrade subdetectors
  - Current Inner Detector (ID) will be replaced by an all-silicon Inner Tracker (ITk)
  - High Granularity Timing Detector (HGTD) to be installed between ITk and endcap calorimeter
  - Electronics upgrades for calorimeter and muon systems



# Radiation challenges for Inner Tracker

- Inelastic hadron-hadron collisions are dominated by soft (low-$p_T$) interactions
  - These events are selected for study by the minimum bias trigger
  - Main source of radiation backgrounds; particularly intense in high-eta regions
- Numerous challenges posed by radiation backgrounds for design of Inner Tracker
  - Radiation exposure lifetime for ITk will be increased tenfold compared to ID
    - Luminosity of 4000 $fb^{-1}$ for HL-LHC running; cf LHC luminosity 350 $fb^{-1}$
  - ITk silicon sensors will be placed closer to regions of greater radiation intensity
    - ITk eta coverage extended to 4; cf ID eta coverage to 2.5
  - Back scattering of neutrons from calorimeters
    - Polyethylene shielding to moderate neutrons
    - HGTD also potential source of back scattering; designed to mitigate impact on ITk

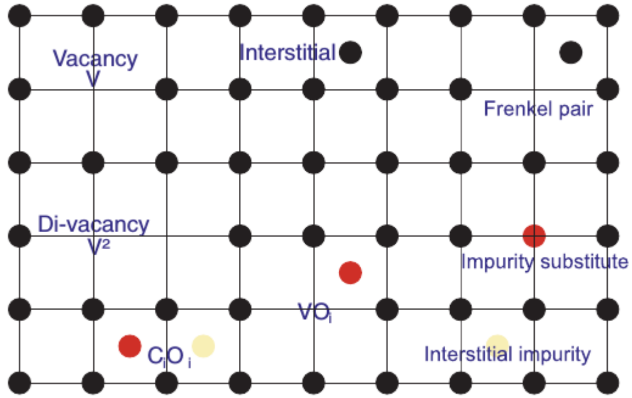


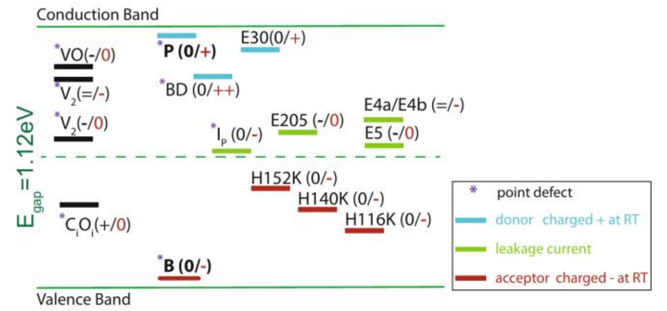



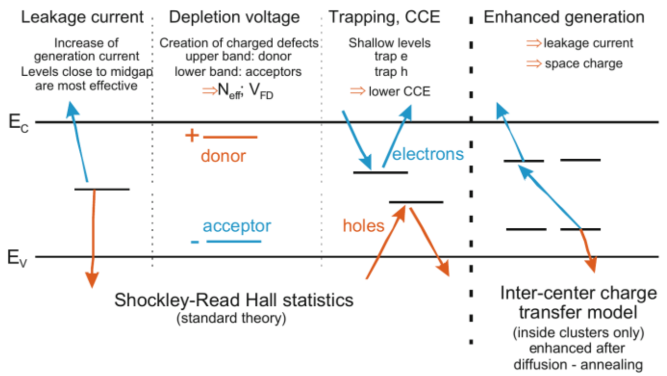
# Radiation damage in silicon sensors



- Most significant radiation-induced damage in a silicon lattice is Non-Ionising Energy Loss (NIEL)
  - Radiation displaces lattice atoms, creates bulk defects
  - Concentration of bulk defects increases with time
- Bulk defects introduce new energy levels in the band gap
  - Close to conduction or valence band: acts as donor or acceptor, changes effective doping concentration
    - NB: Deliberate doping can produce desired defects
  - Shallow levels: traps electrons + holes, reduces charge collection efficiency (CCE)
  - Close to mid-gap: increases generation of leakage currents
- Annealing increases mobility of defect atoms
  - Can be used to reduce concentration of bulk defects, recover sensor performance

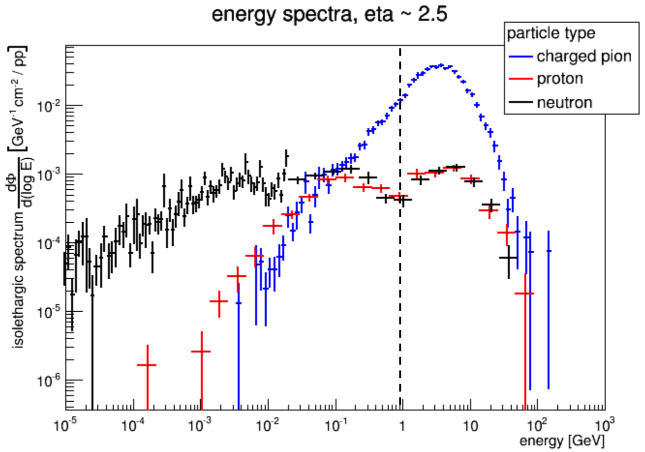


# Silicon damage fluence

- **Silicon damage (1 MeV) fluence $\Phi_{eq}$** is a proxy for NIEL in silicon
  - Used to model evolution of leakage currents + depletion voltages, which allow us to anticipate detector performance over its lifetime
  - Commonly scored in radiation simulations
- Silicon damage fluences calculated by weighting particle of particular type + energy with silicon damage factors
  - Damage factors scale to equivalent of 1 MeV neutron in silicon
  - Damage factors are combination of test beam data + calculations from nuclear interaction models

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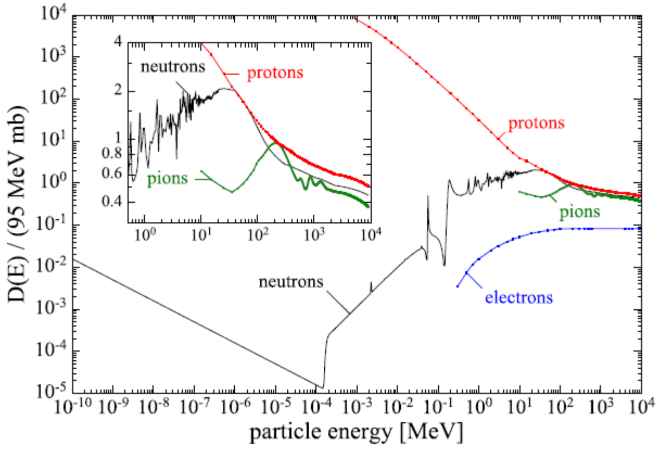


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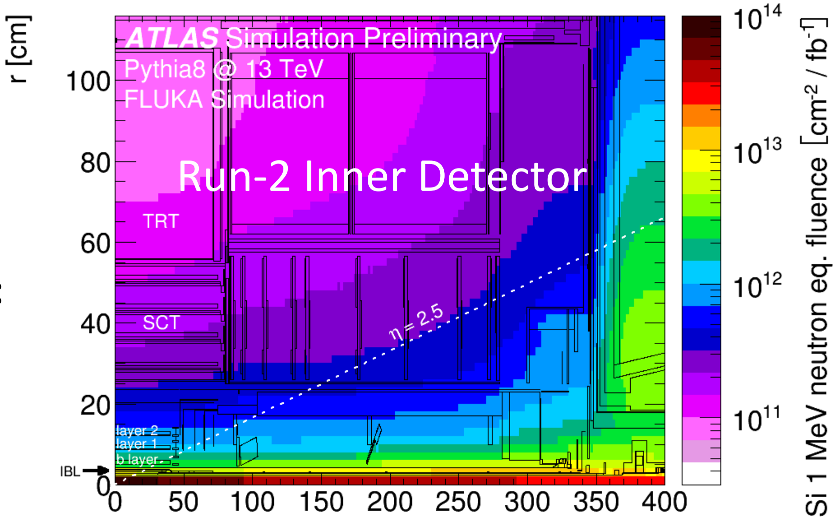


# ATLAS radiation simulations

- Bulk of ATLAS radiation simulation work done with FLUKA
  - FLUKA also used by other LHC experiments + CERN Radiation Protection (RP)
  - ATLAS previously also used FLUGG and GCALOR
  - GEANT4 being used increasingly for radiation simulations
  - Different MC codes enable mutual cross-check
- Standalone FLUKA model with simplified version of full ATLAS detector geometry and material (including calorimeters, shielding, beam line)
  - Different detector layouts can be implemented + studied relatively quickly (compared to full ATLAS GEANT4 simulation for physics)
  - Simplified geometry cannot accommodate detailed physics studies
  - Same FLUKA model used for radioactivation calculations by CERN RP
  - Minimum-bias events for proton-proton collisions used as input
- Other commonly scored quantities in radiation simulations
  - **Ionising dose** important for predicting damage in electronics
  - **Fluence of hadrons > 20 MeV** to estimate rate of Single Event Effects in electronics
  - **Charged particle fluence** to estimate occupancies + data rates
  - **Radioactivation** estimates can dictate procedures for cavern access and detector installation + maintenance

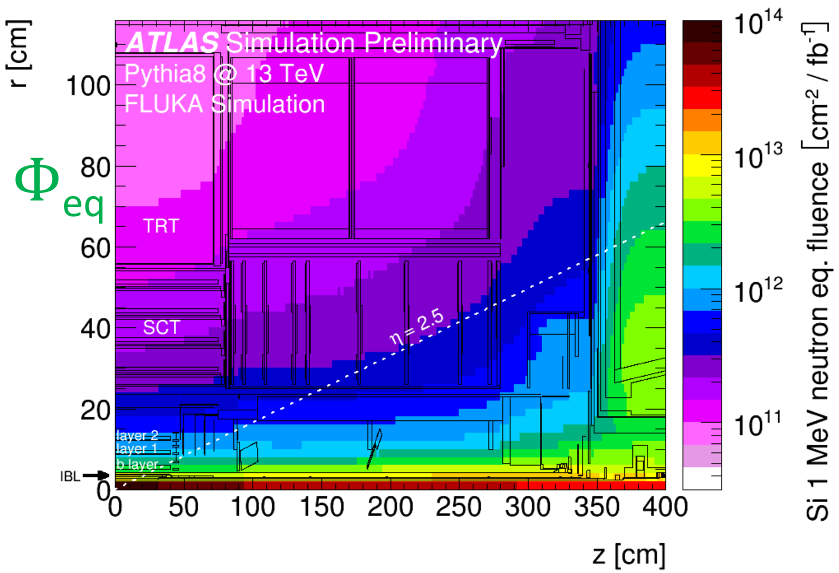
# Benchmarking of Run-2 results

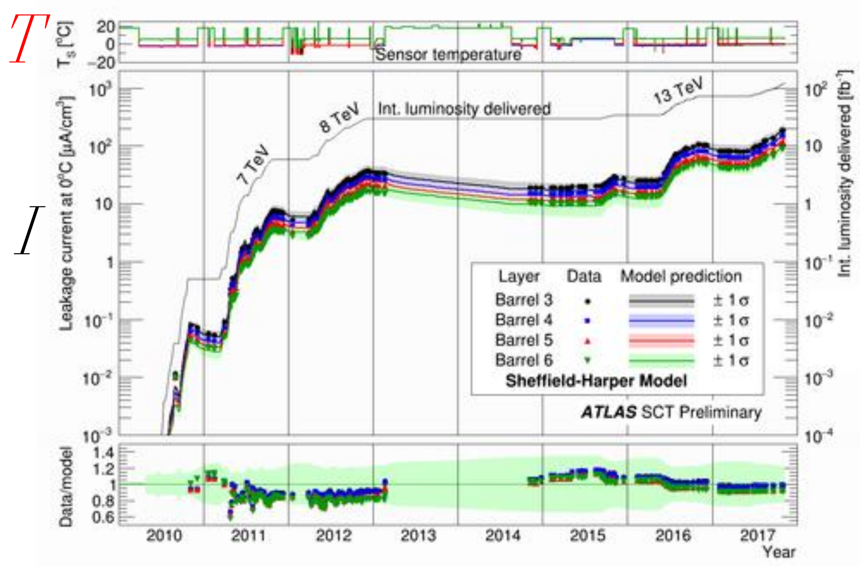


- Leakage currents are an inherent feature of silicon sensors
  - Silicon sensors are doped to produce p-n junctions
  - Differences in doping concentration result in electric field across the depletion zone of the p-n junction
  - Thermally generated charge carriers will drift in this field, leading to leakage current
- Leakage current models (e.g., Sheffield-Harper) predict evolution of these currents over lifetime of detector

$$I(t, T, \Phi_{eq}) = I_0 + \alpha(t, T)\, \Phi_{eq}\, V$$

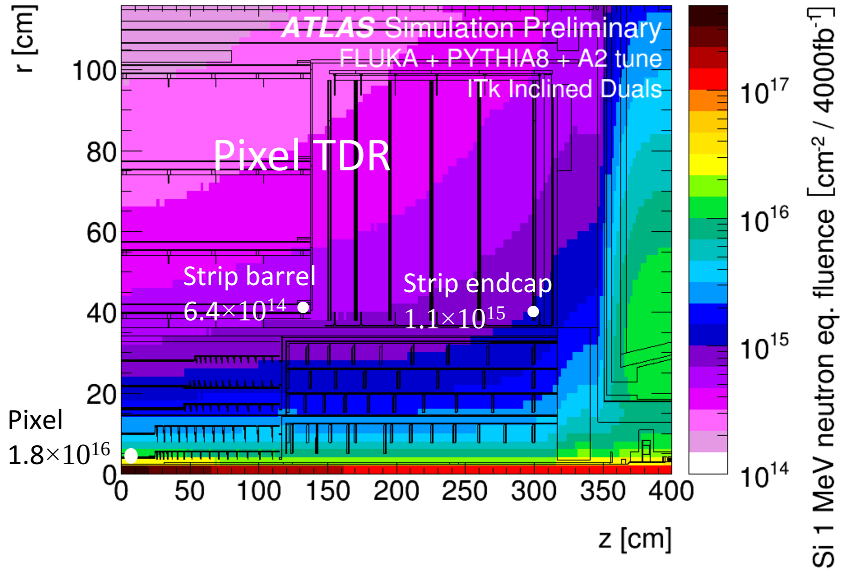
  - Fluence predictions $\Phi_{eq}$ feed into leakage current model
  - Temperature annealing effects also included
- Comparison of predictions with leakage current measurements gives good agreement
  - Other benchmarking comparisons with Radiation Monitor measurements also give good agreement
  - Gives confidence in radiation simulation predictions for Upgrade scenarios

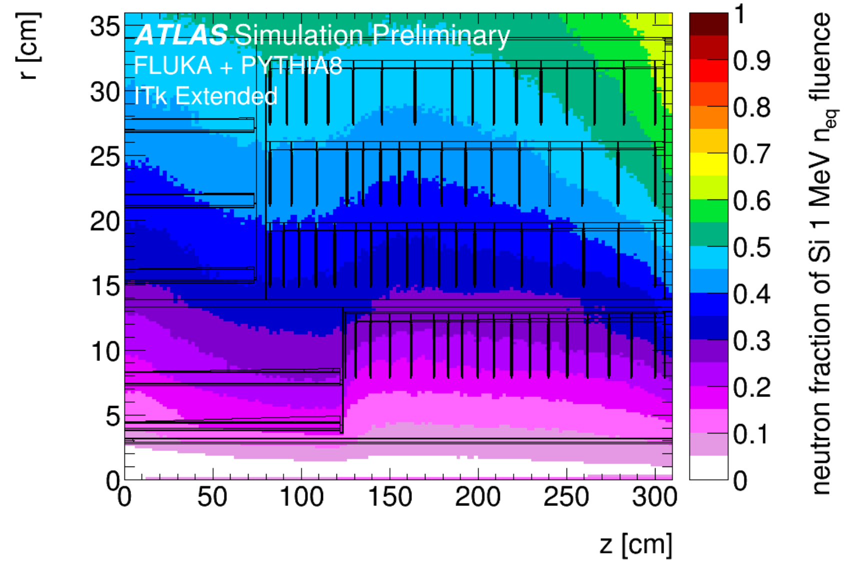


# Upgrade detector studies

- Fluence predictions for Upgrade detector updated as ITk layout evolves
  - Radiation simulations provide feedback link between physicists and engineers
  - Latest published results: Pixel TDR, June 2018
  - Many other alternative layouts studied, not published
  - Latest ITk layout still evolving with latest engineering designs + trigger schemes
- Maximum fluence values in ITk regions used for irradiation tests of sensors + chips
- Other dedicated studies on particular topics
  - Particle contribution to silicon damage fluences
  - Impact of placement of services on fluences in ITk and downstream subdetectors
  - HGTD shielding design
  - Comparison of GEANT4 with FLUKA for radiation simulations



# LHC radiation effects workshops



- Series of workshops devoted to discussing effects of radiation on performance of LHC detectors
  - 31st RD50 workshop, November 2017
  - 1st workshop on radiation effects in the LHC experiments, April 2018
  - 2nd workshop on radiation effects in the LHC experiments, February 2019
  - CERN Yellow Report in preparation

# Summary

# Summary

- Long-term exposure to radiation environments can lead to performance degradation in detector systems
  - Simulations of radiation environments can provide an important input in detector design to mitigate such issues
- Role of radiation simulations in Radiation Resilient Ultrasonic Sensors (RRUS) project
  - Full simulation of DCF irradiation test provided accurate dosimetry in PVDF sensor material
  - Simulation studies of shielding design to mitigate against effects of radiation
- Role of radiation simulations in ATLAS Upgrade project
  - Provide feedback link between physicists and engineers in design of the Upgrade detector
  - Dedicated studies to optimise detector layout and thereby reduce radiation levels in critical regions
  - Predictions of radiation levels facilitate modelling of detector performance evolution