Radiation environment simulation at the LHC experiments and detector damage studies.

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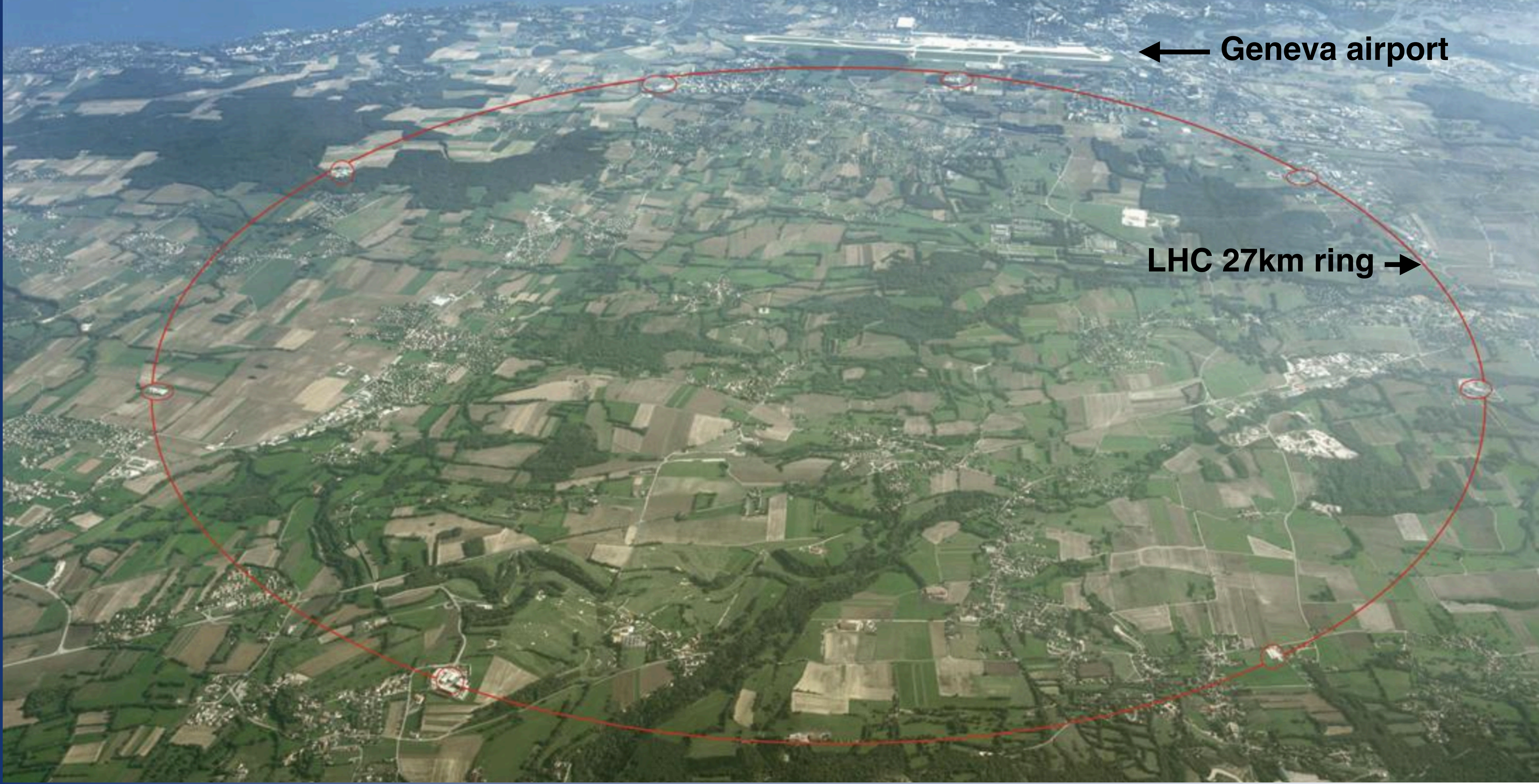
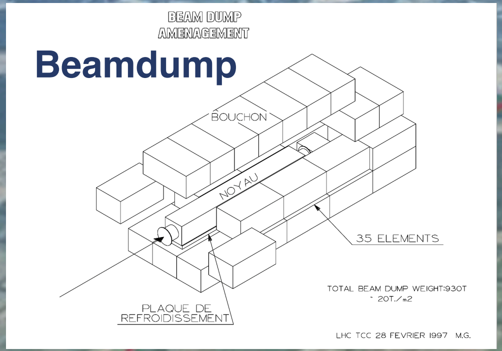
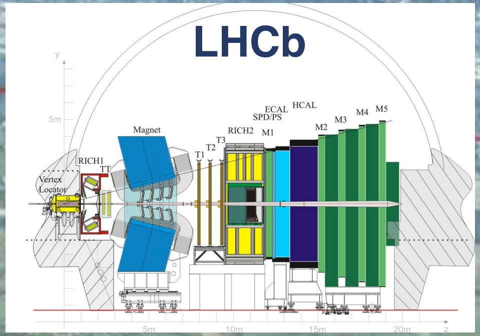
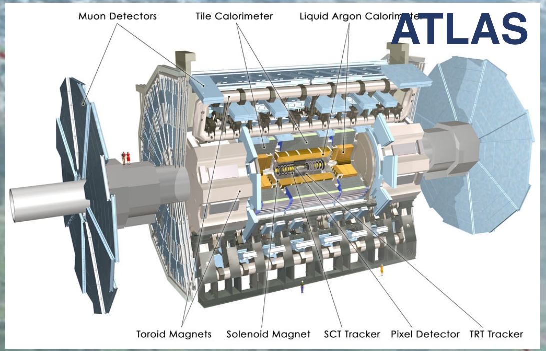
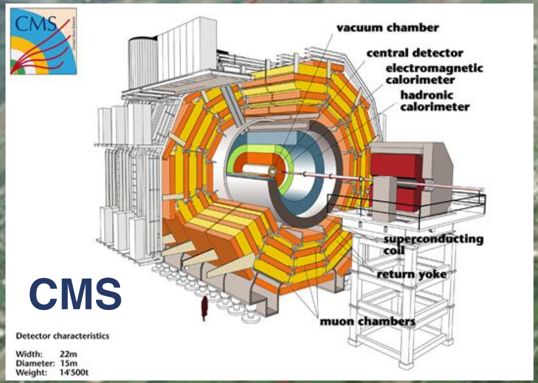

Geneva airport
LHC 27km ring

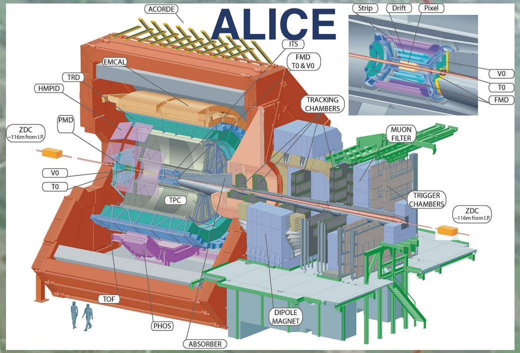


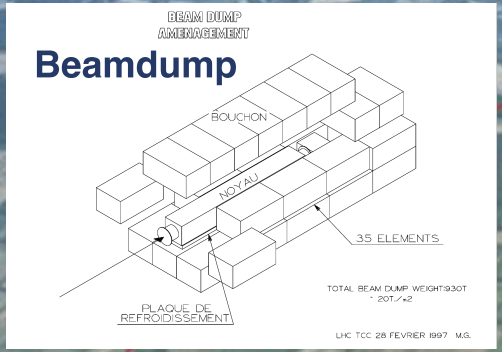


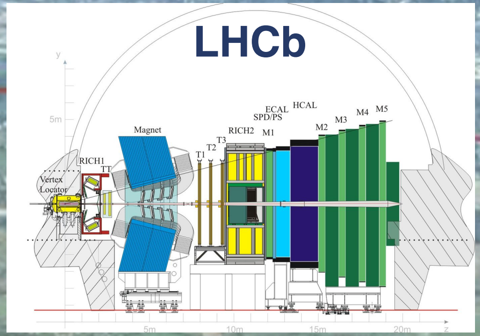


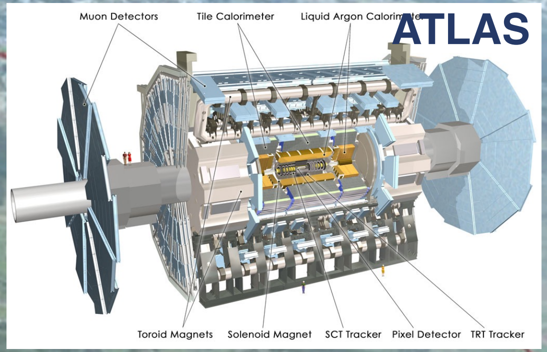


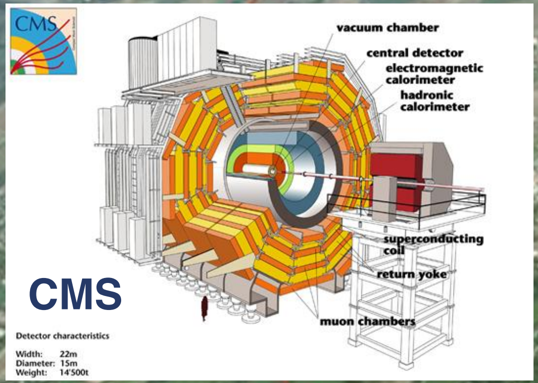
- 6.5 TeV proton beams
- 2808 bunches
- 10^{11} protons per bunches
- 10^{9} collisions per second

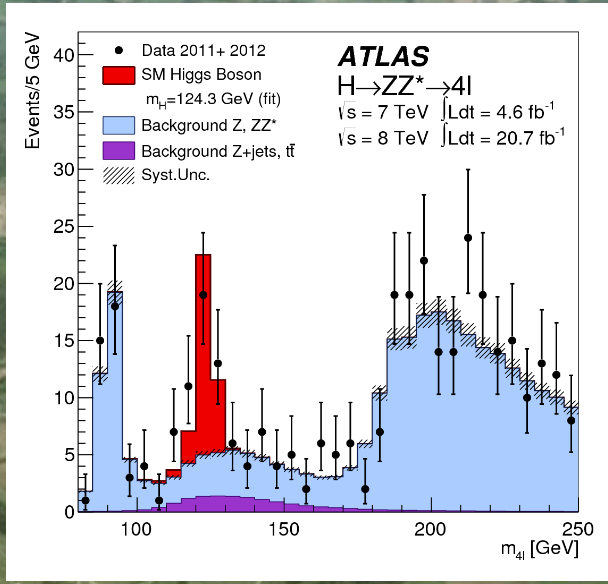


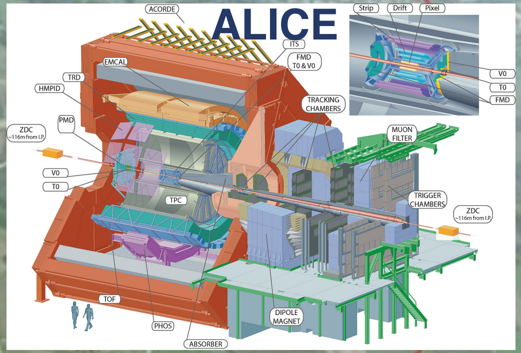




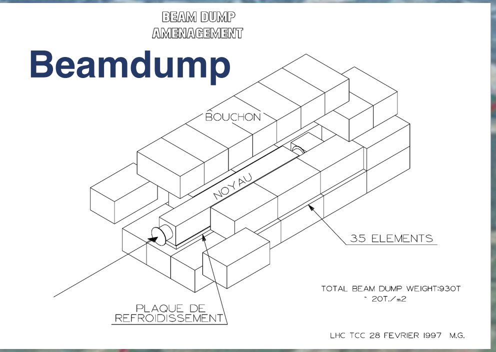


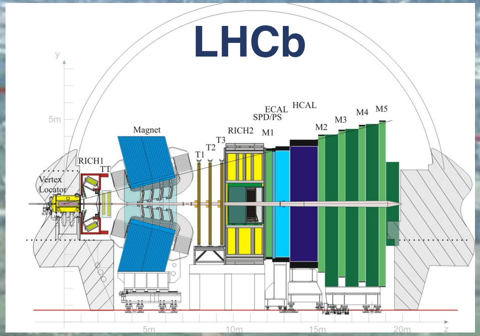


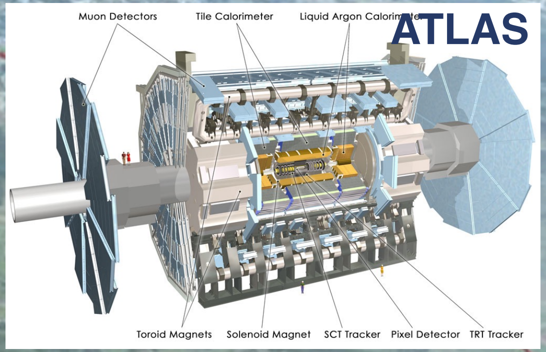


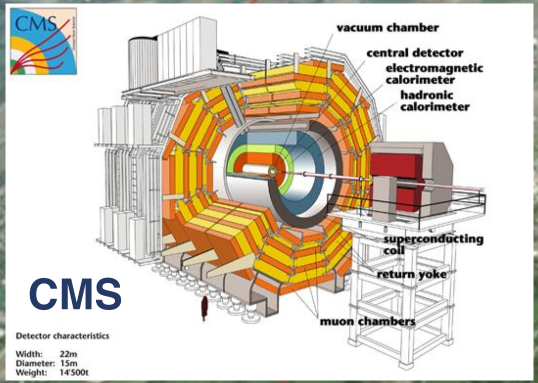


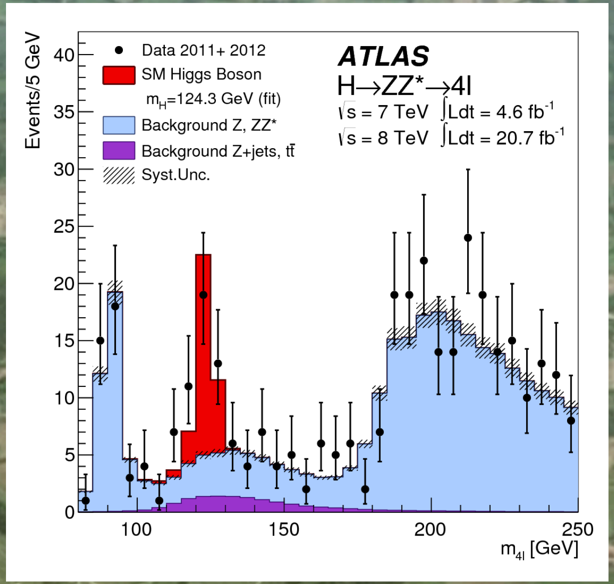
What it's all about!

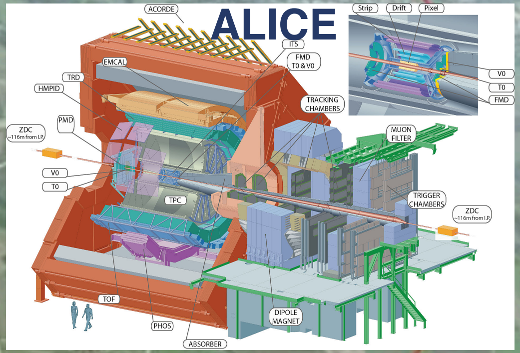












But LHC physics comes at the cost of generating unprecedented levels of radiation backgrounds. It is crucial to understand how these radiation backgrounds impact detector systems so they can be designed, tested and qualified.

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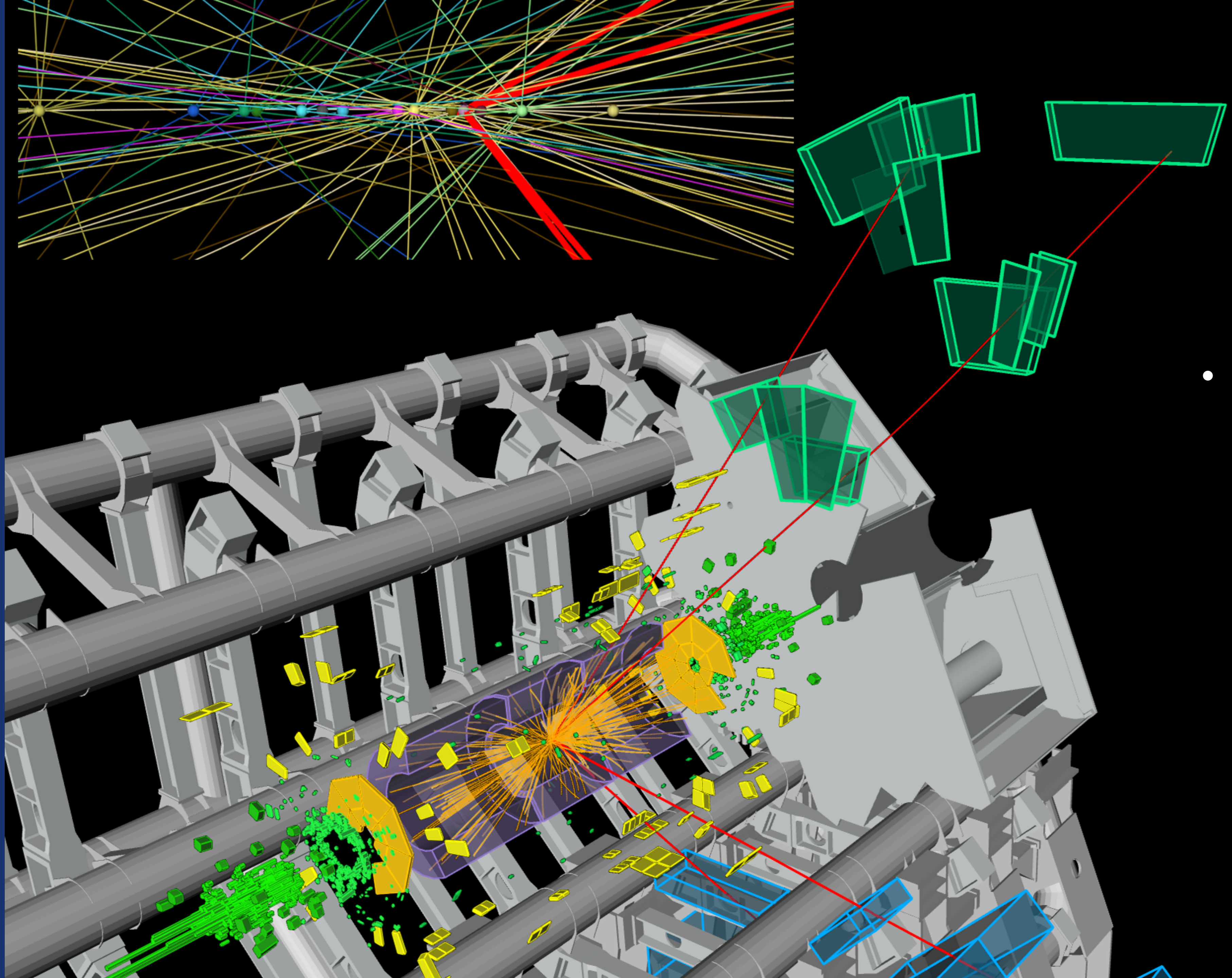
ATLAS EXPERIMENT
http://atlas.ch

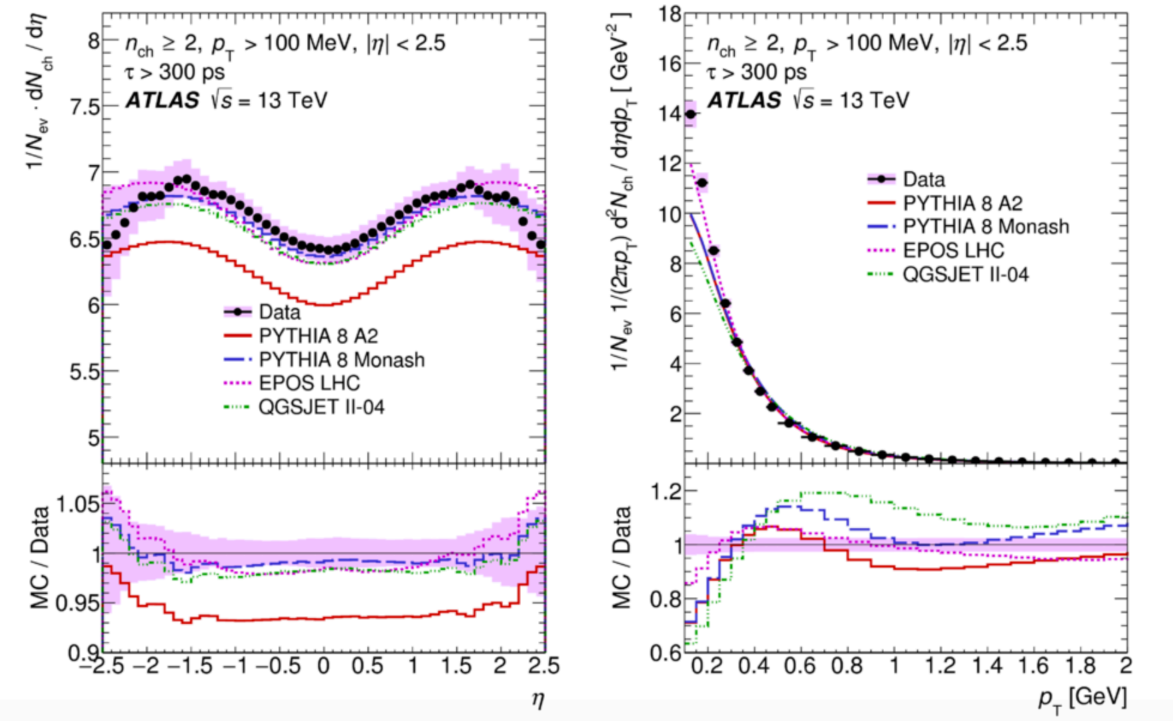


- There are ~10^9 inelastic pp collisions per second, and each collision produces ~100 particles, mainly pions.

Simulating radiation environments.

- A main driver of the radiation backgrounds in ATLAS is the proton-proton (pp) collisions.
- So we need reliable event generators that can describe the full inelastic processes of pp interactions, e.g. Pythia8, Phojet.
- At the LHC our measurements of such events are called “minimum bias”, with the physics processes dominated by soft QCD.
- Pre LHC, we assumed 30% on the event generator uncertainties in terms of particle production.

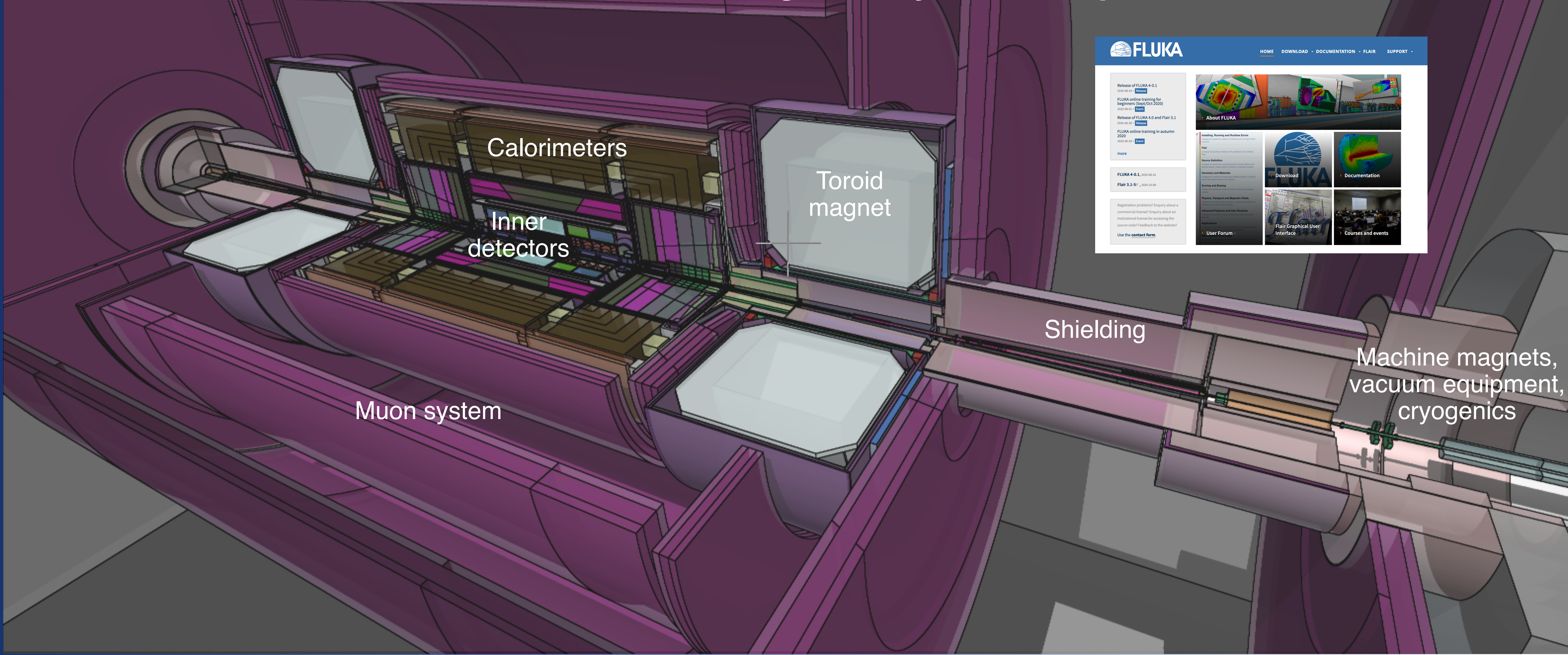
Charged particle multiplicities as a function of pseudo-rapidity (left) and transverse momentum (right).



The ATLAS Collaboration, Charged-particle distributions at low transverse momentum in $\sqrt{s}$=13 TeV pp interactions measured with the ATLAS detector at the LHC, Eur. Phys. J. C volume 76, Article number: 502 (2016)

Queen Mary
University of London

The particle (4-vector) output from an event generator is fed into high fidelity Monte Carlo simulation codes such as FLUKA and GEANT4 for particle transport. We therefore need to create a simulation geometry for the experiment.



Simulating radiation environments.

Monte Carlo Particle Transport

- First make sure your simulation package choice has the physics you want and is appropriate for your problem.
- Eg FLUKA:
  - **60 different particles + Heavy Ions**
  - Nucleus-nucleus interactions from Coulomb barrier up to 10000 TeV/n
  - Electron and μ interactions 1 keV – 10000 TeV
  - Photon interactions 100 eV - 10000 TeV
  - Hadron-hadron and hadron-nucleus interactions 0–10000 TeV
  - Neutrino interactions
  - Charged particle transport including all relevant processes
  - Transport in magnetic fields
  - Neutron multigroup transport and interactions 0 – 20 MeV
  - Analog calculations, or with variance reduction

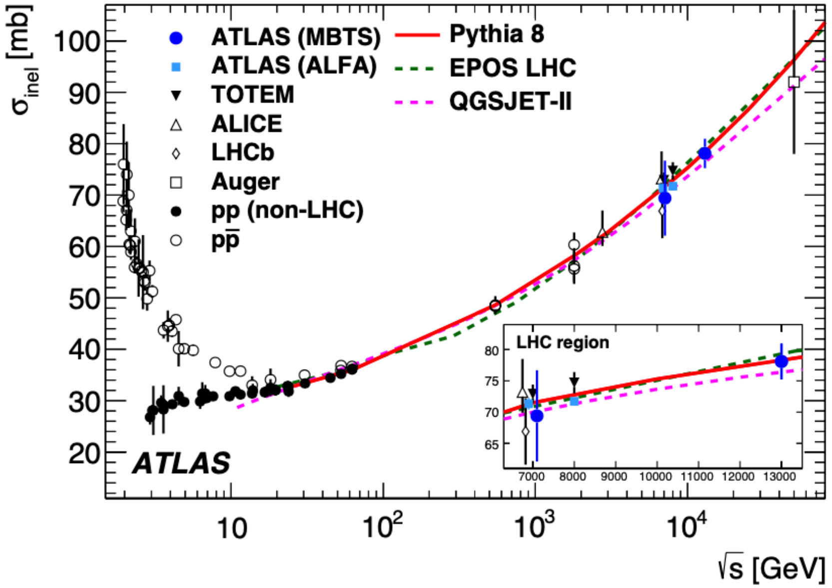
Simulation of fluences and doses: Monte Carlo Particle Transport

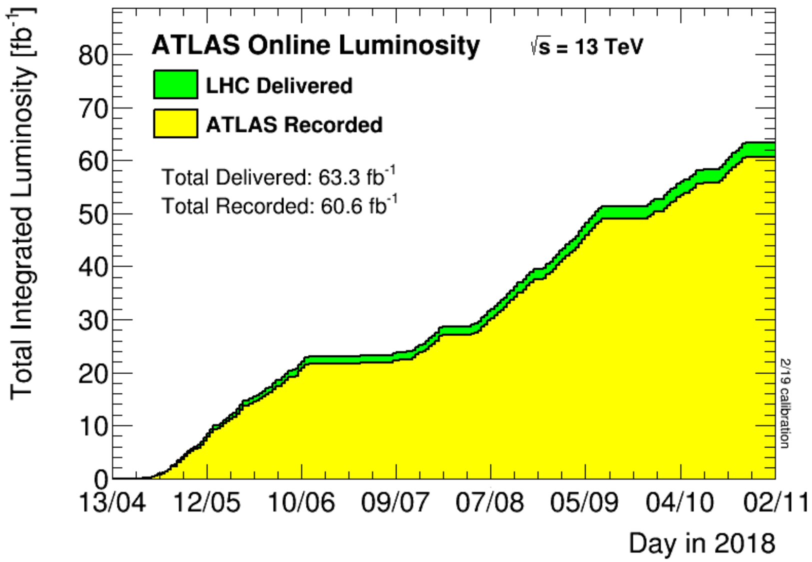
- **Is Monte Carlo simulation necessary?** Other methods include: solving numerical transport equations; use of look-up tables?
- MC simulation **is essential** because:
  1) The complexity of the high energy hadron and electromagnetic cascades, which are not always theoretically well understood.
  2) Multi-region, multi-material three-dimensional geometries, often including magnetic fields, impose difficult boundary conditions.
  3) Often want to study statistical fluctuations in the cascades event by event, not some average quantity.

Simulating radiation environments.

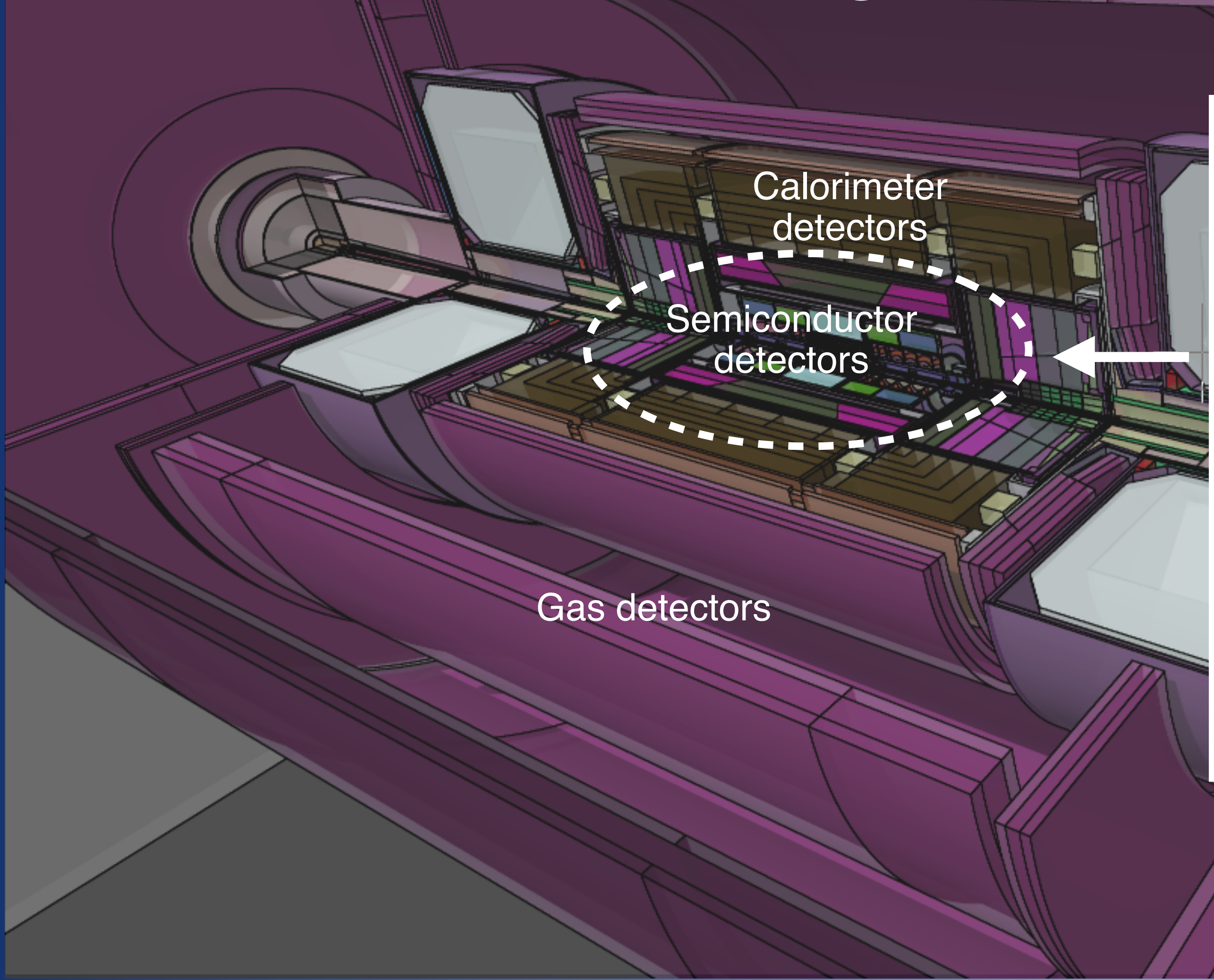
- Simulation codes usually give "fluence per event", we typically want to convert to fluence per second (or per year or per fb-1).

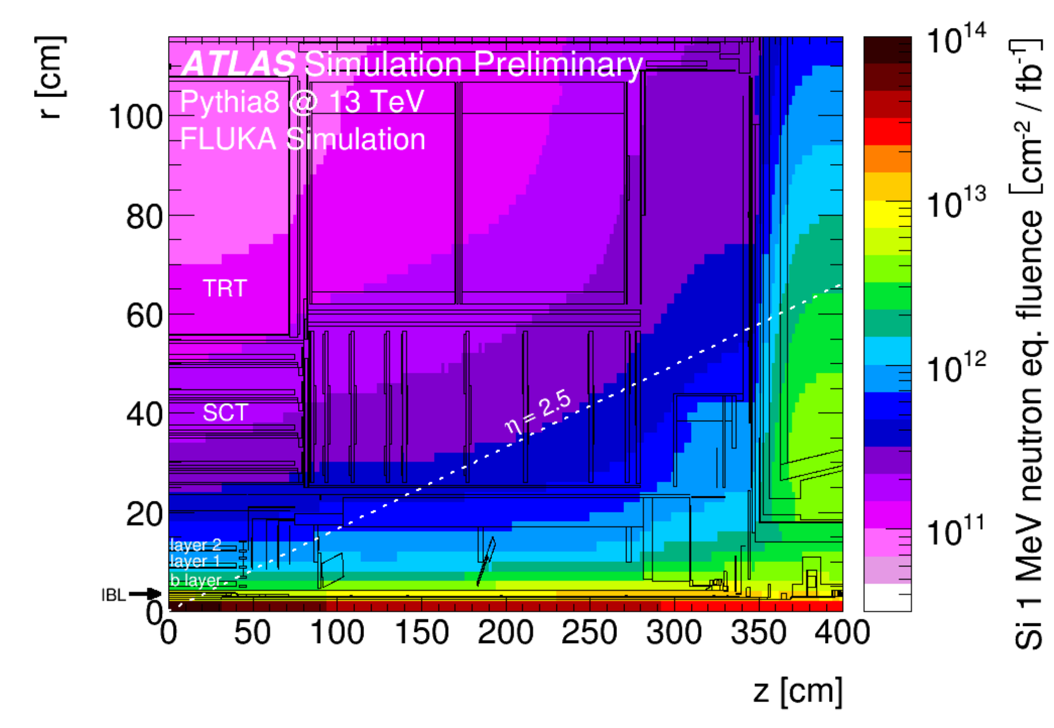
$$N_{ev} = \sigma_{inel} \times L_{del}$$





From the simulations we obtain the radiation damage quantities of interest: ionising dose; neutron fluence; SEE flux, etc..





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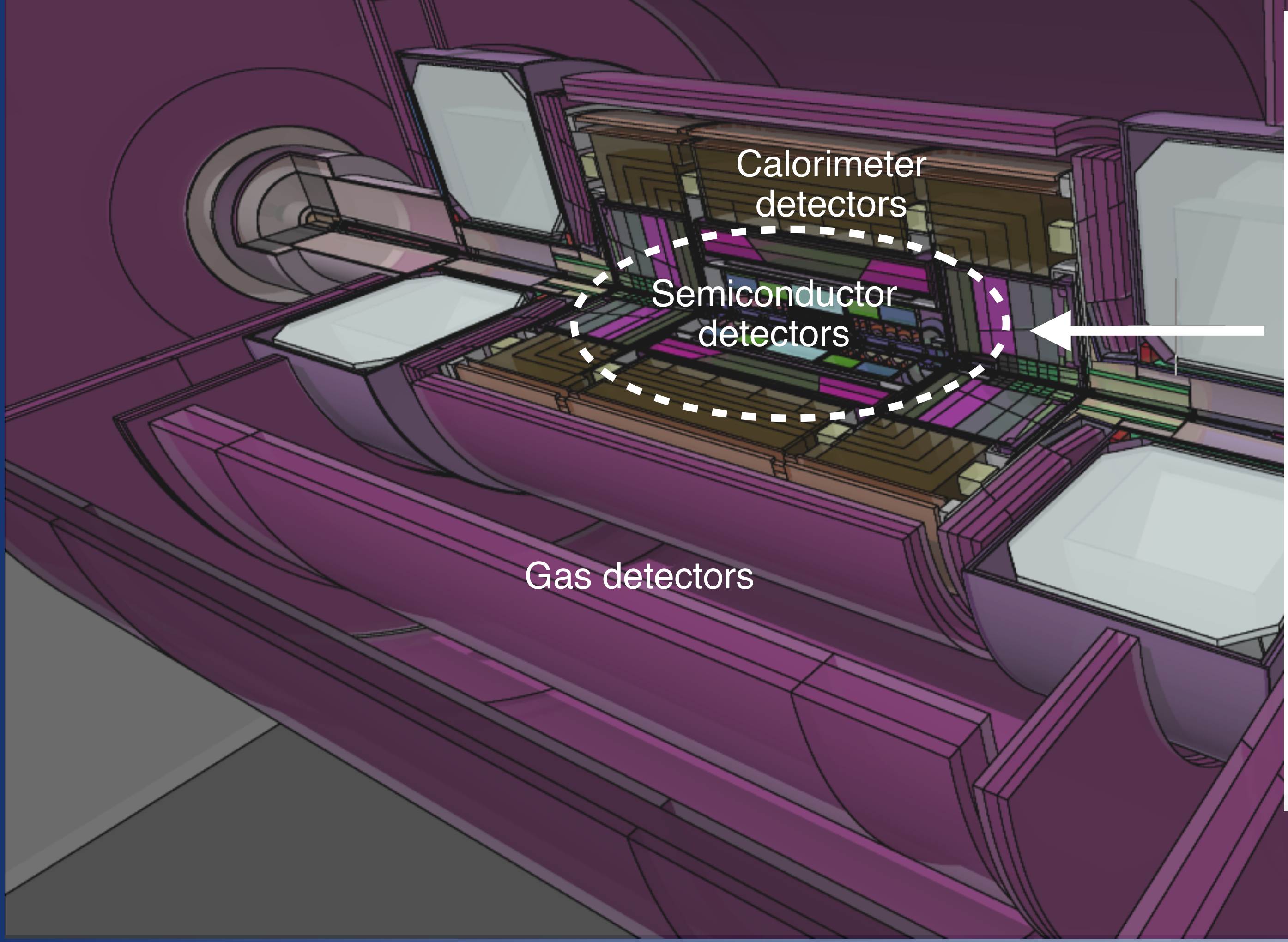
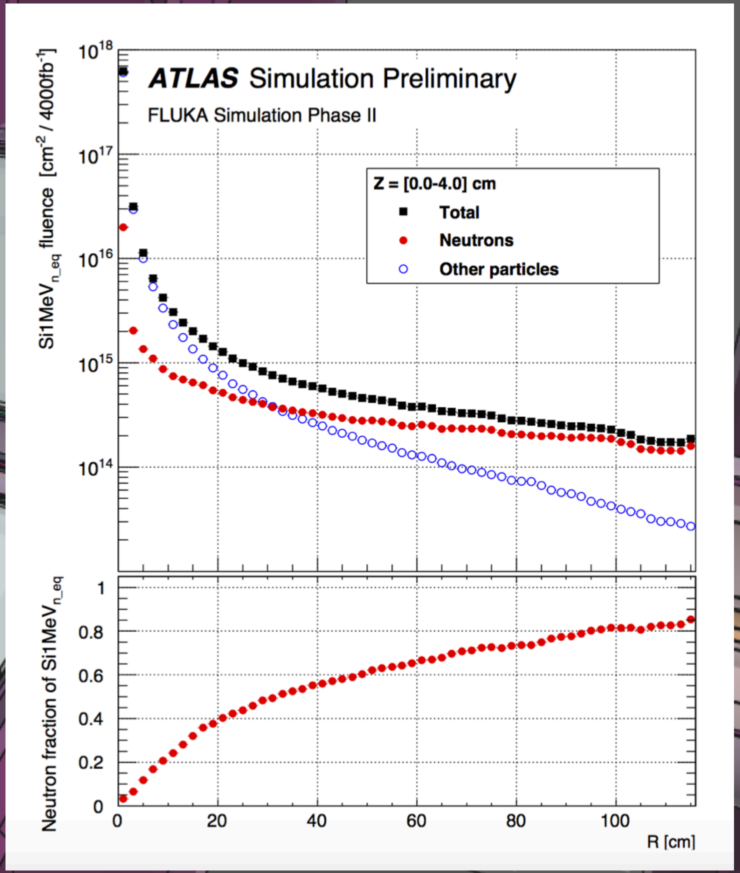
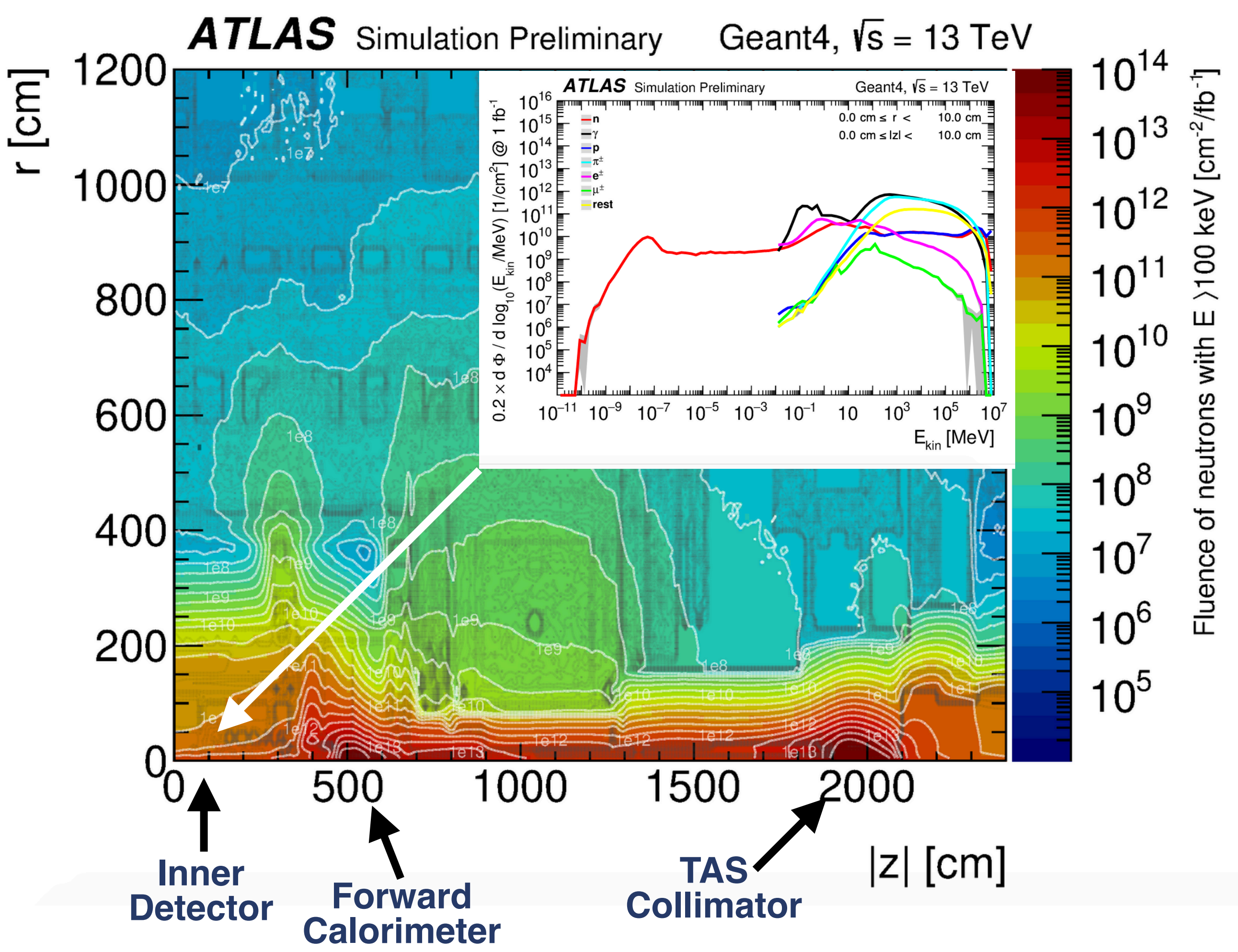




Simulating radiation environments.

- Athena G4 now being used for radiation background studies on ATLAS.
- Note, the resulting hadron cascades in the calorimeter and machine material gives rise to a complex situation where “neutron sources” are created in regions of intense cascades. Only advanced codes like FLUKA and G4 can treat these properly.



Simulating radiation environments.

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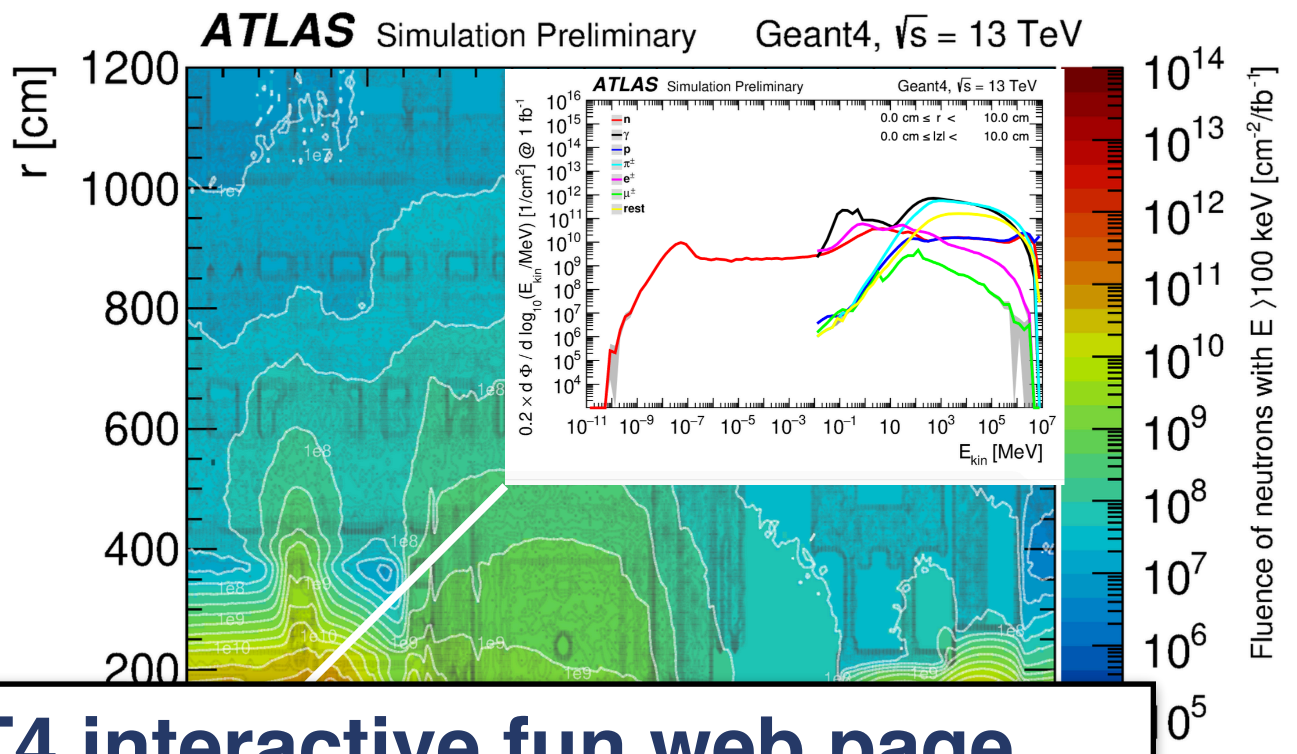

See ATLAS's GEANT4 interactive fun web page for exploring fluence, dose, spectra etc.

https://twiki.cern.ch/twiki/pub/AtlasPublic/RadiationSimulationPublicResults/WebRadMaps_Zoom_R2_public.html

(Developed by Sven Menke, MPI.)

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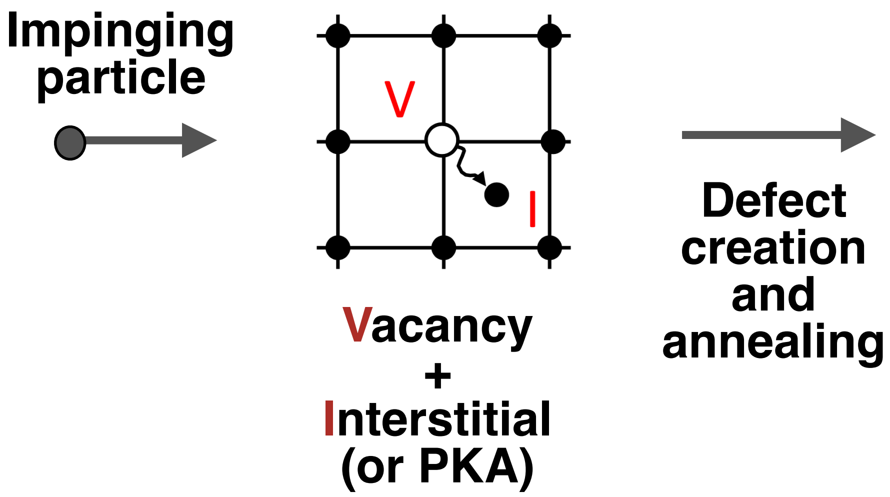
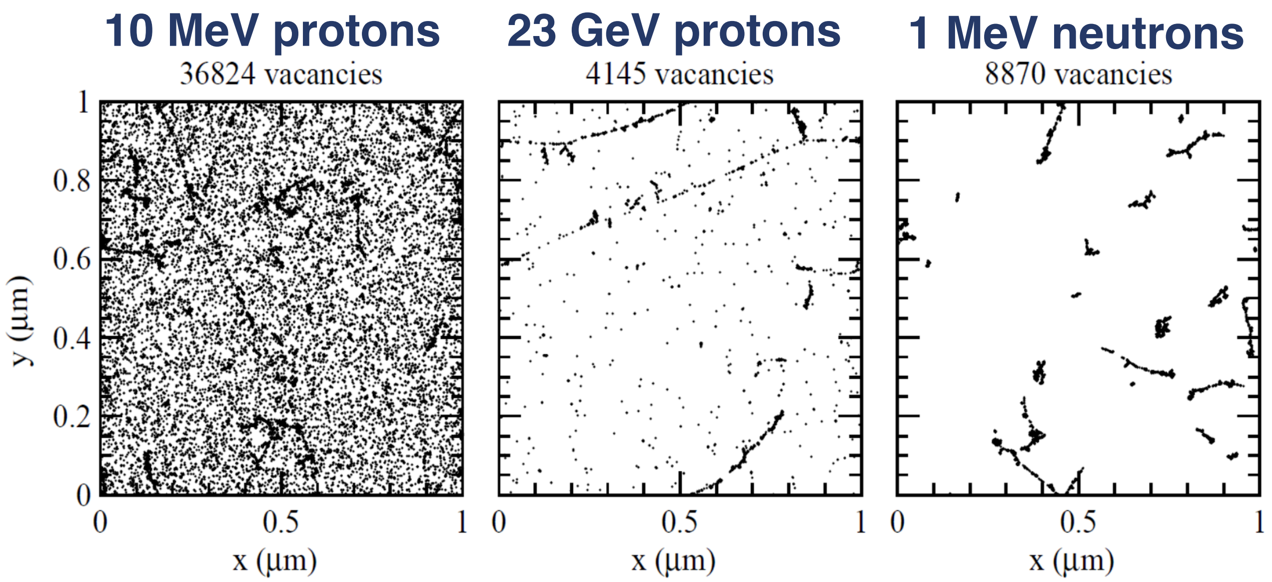
Displacement damage

- Particles interacting in matter will result in the displacement of atoms from their lattice sites. In semiconductors this leads to point-like or clusters of defects in the bulk material and a degradation of device electrical/optical performance.





The number and type of defects depend on the incoming particle type and energy.

Displacement damage

- If the number and type of defects depend the particle type and energy, doesn't this make quantifying radiation damage extremely difficult for the complex LHC radiation environments that cannot be replicated in the laboratory?
- Enter the non-ionising energy loss (NIEL) hypothesis: that the radiation damage effects scale with the NIEL:

$$NIEL(E) = \frac{N_A}{A} \int_{E_D}^{E_R^{max}} E_R \; L(E_R) \; \frac{d\sigma(E, E_R)}{dE_r} \; dE_R$$

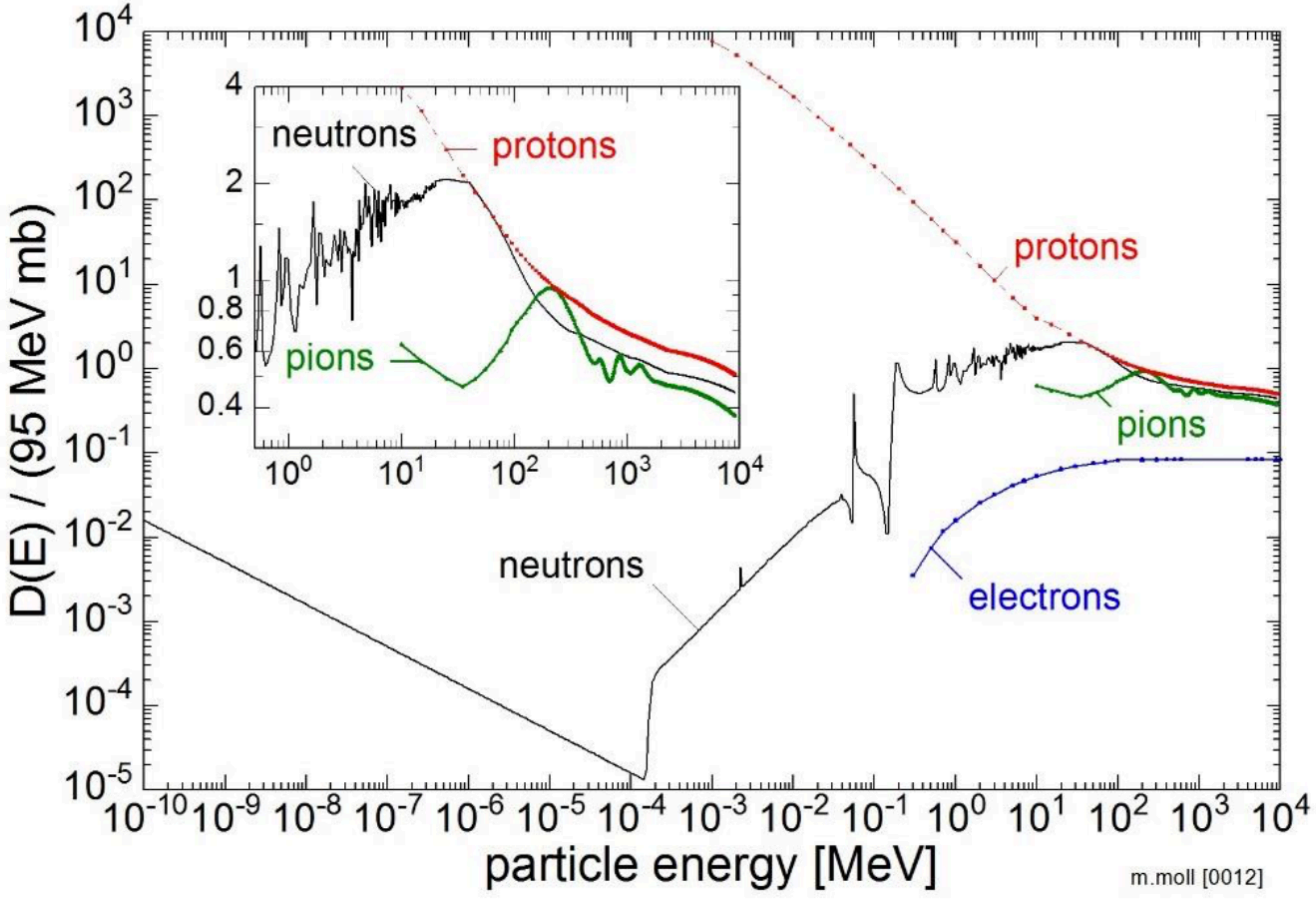
- **E** = energy incoming particle.
- **E_R** = energy recoiling atom.
- **$d\sigma(E, E_R)/dE_R$** = differential cross section for particle with energy E to create recoil with energy E_R.
- **$L(E_R)$** = partition factor giving fraction of E_R going into further displacements.
- **N_A** = Avogadro constant
- **A** = atomic mass

- Note units are MeV-cm^2/g. Multiplying by the particle fluence Φ (cm^{-2}) gives the displacement dose. Often NIEL expressed in units of MeV-mb and called displacement cross section.

Displacement damage

- Common to normalise the NIEL, or the displacement damage cross section D(E), to that of a 1 MeV neutron (95 MeV mb), creating energy dependent "hardness factors".
- Now we can relate the radiation NIEL damage from different particle types and energies.

$$\Phi_{eq}(1MeV) = \frac{\int \phi(E)D(E)dE}{D(1MeV)}$$



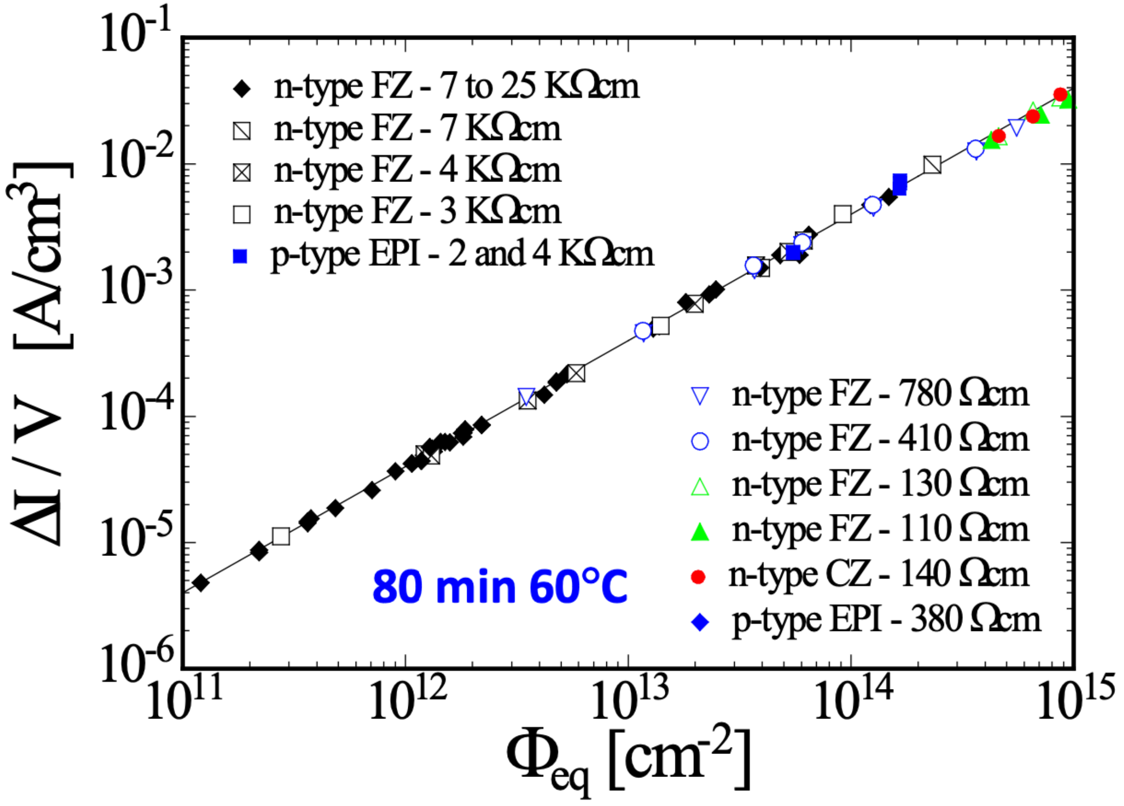
https://rd50.web.cern.ch/NIEL/default.html

Displacement damage

- But does it work?
- For leakage current seems to work amazingly well!

$$\frac{\Delta I}{V} = \alpha \, . \, \Phi_{eq}$$

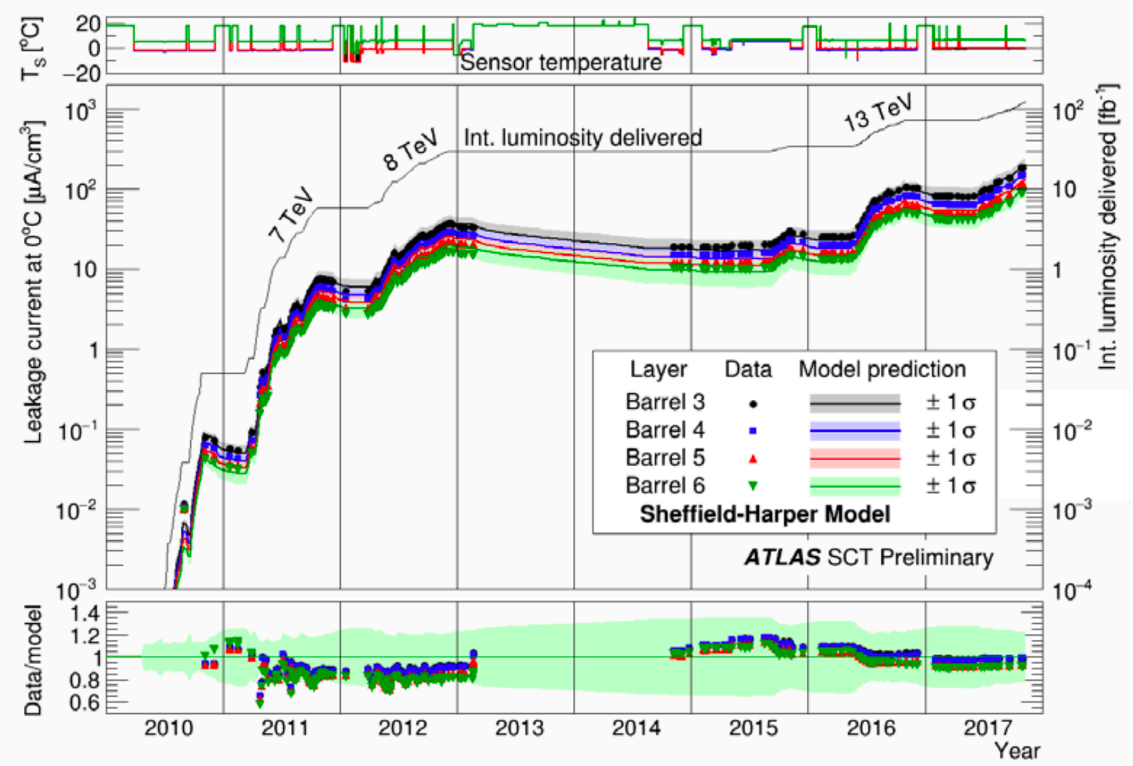
- Do we care about leakage currents? Yes! Consequences for: power requirements, cooling; noise, etc.



Leakage current measurements scale nicely with 1 MeV neutron equivalent fluence for a wide range of sensor types and resistivities.

Displacement damage

- We can use this NIEL scaling and parameterise our understanding of annealing to develop predictive models, such as the Sheffield-Harper leakage current model.
- By including also the simulated 1 MeV neutron fluence, we can now predict performance.



PhD student modelling the SCT leakage currents increasing due to radiation damage. →

$$I_n(T_{\rm ref}) \equiv \sum_{i=1}^{n} g_{n,i} \cdot \alpha(T_{\rm ref}) \cdot \delta\Phi_i^{\rm eq} \quad (A.4)$$

$$g_{n,i} = \sum_{k=1}^{5} \left\{ A_k \frac{\tau_k}{\Theta_A(T_i)\delta t_i} \left[1 - \exp\left(\frac{-\Theta_A(T_i)\delta t_i}{\tau_k}\right)\right] \exp\left(-\frac{1}{\tau_k} \sum_{j=i+1}^{n} \Theta_A(T_j)\delta t_j\right)\right\} \quad (A.5)$$

where $\alpha(T_{\rm ref} = 20°{\rm C}) = (4.81 \pm 0.13) \times 10^{-17}$ A/cm is the current-related damage constant.

$$\Theta_A(T) = \exp\left(\frac{E_I}{k_B}\left[\frac{1}{T_{\rm ref}} - \frac{1}{T}\right]\right), \quad E_I = 1.09 \pm 0.14\,{\rm eV}. \quad (A.6)$$

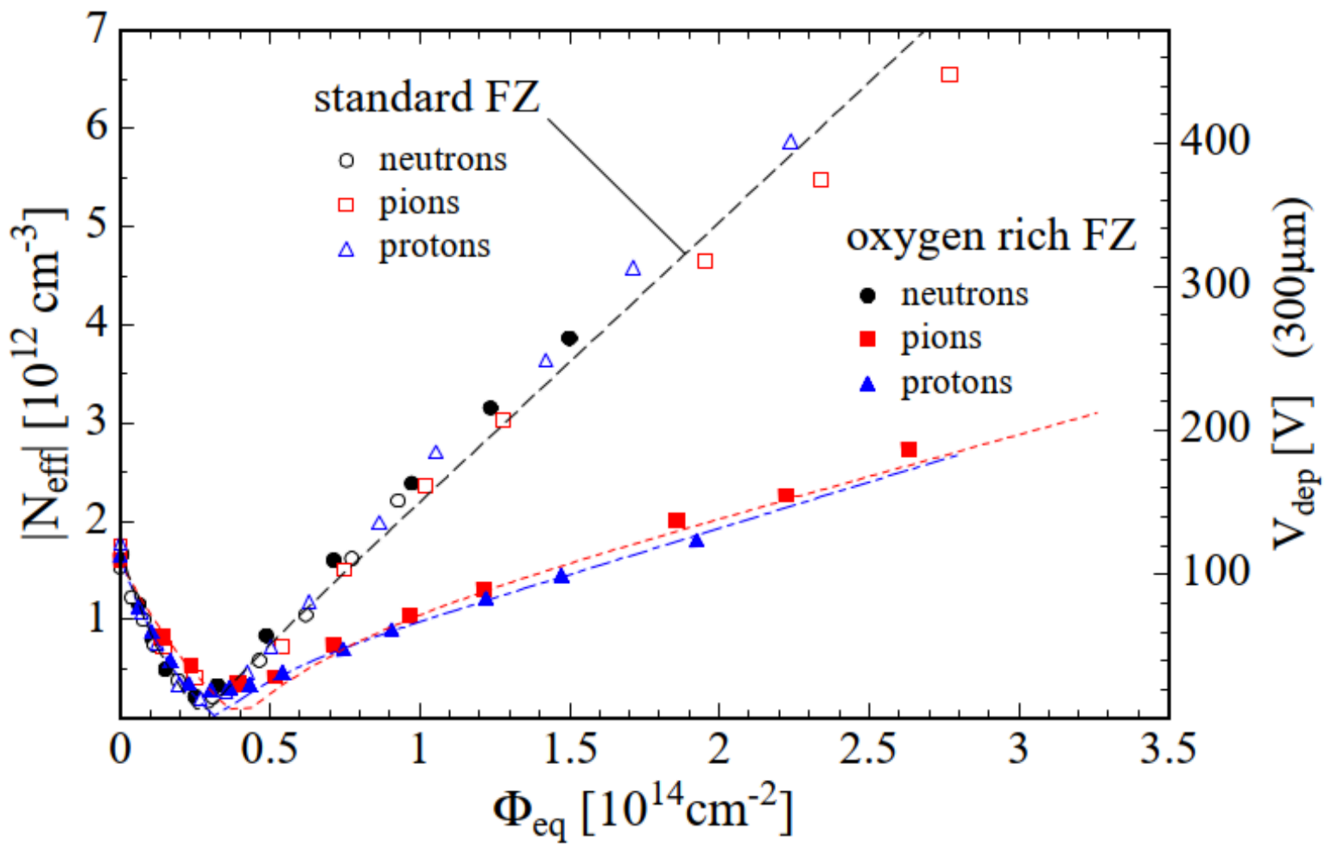
←

Parameters at T_{ref}=20°C

k	τ_k [min]	A_k
1	$(1.2 \pm 0.2) \times 10^6$	0.42 ± 0.11
2	$(4.1 \pm 0.6) \times 10^4$	0.10 ± 0.01
3	$(3.7 \pm 0.3) \times 10^3$	0.23 ± 0.02
4	124 ± 2.5	0.21 ± 0.02
5	8 ± 5	0.04 ± 0.03

Displacement damage

- We can also try to model other device properties such as evolution of depletion voltage.
- However not everything scales with NIEL, see all known example of oxygen enriched sensors.

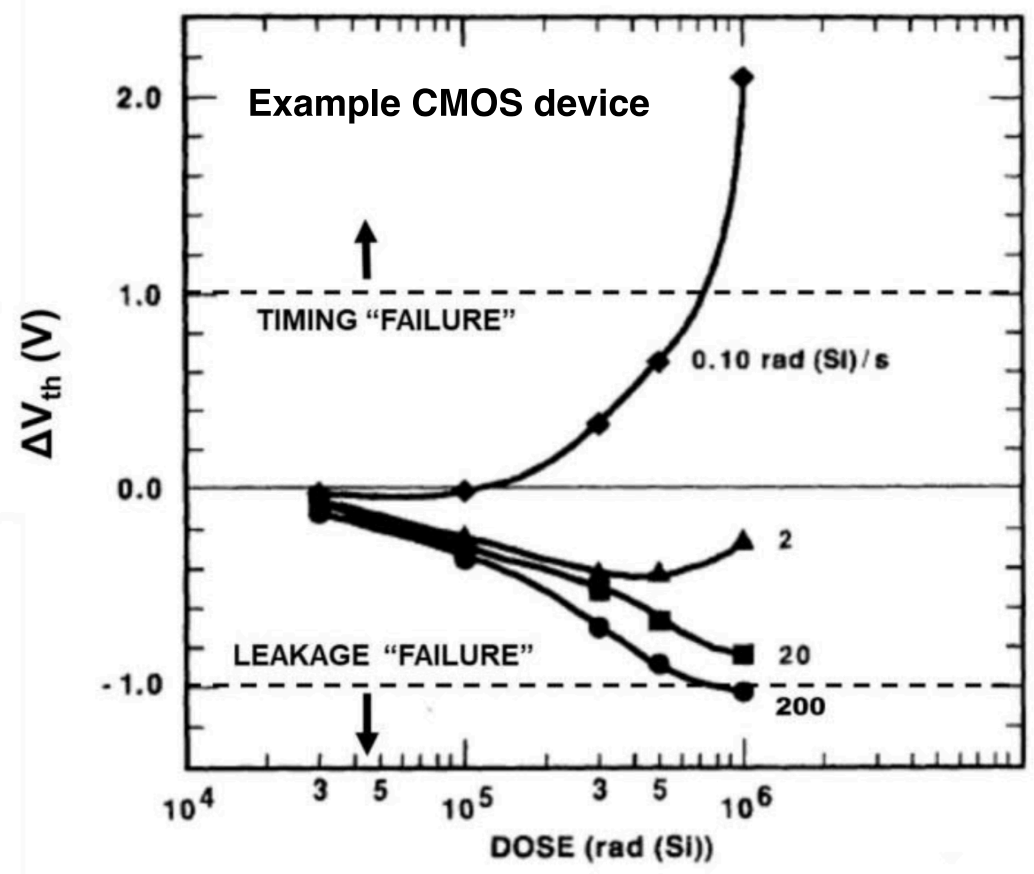


V_{dep} is dependent on particle type for oxygen-rich silicon. For charged hadrons, ~3 times smaller increase in N_{eff}. For O_2 enriched. For neutrons, no change.

TID effects

- Total Ionising Dose (TID) effects are very important for degradation in electronics. Values at the LHC range from a few Gy up to several MGy.
- Complex build up and trapping of charge in the insulating oxide layers and the interfaces with bulk silicon.
- On CMOS leads to: shifts in threshold voltages; decreased current gains etc.
- Tricky to model, the effects are dependent on temperature, bias and dose rate.
- We can irradiate devices at the application temperature and biased. However the lifetime of a detector system may be up to ten years, which means TID testing at irradiation facilities has to be done with dose rates much higher than those found in the LHC radiation environments.

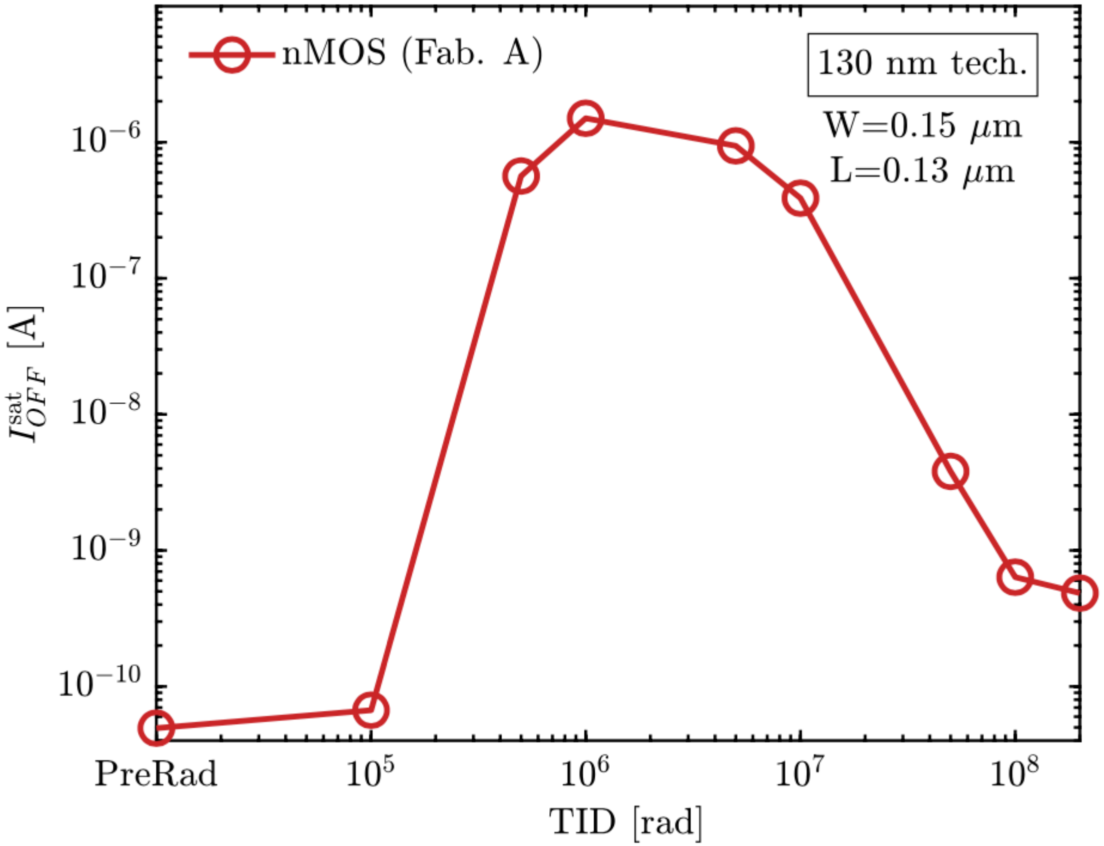
D.M. Fleetwood and H.A. Eisen, *IEEE Trans. Nucl. Sci.* **50** (2003)



Irradiating at high dose-rates leads to negative shifts in the threshold voltage, because the buildup of oxide-trap charge dominates. Irradiating at much lower dose-rates allows the oxide-traps time to anneal and interface-traps become dominant along with positive shifts in the threshold voltage.

TID effects

- Example of TID effects impacting LHC electronics.
- Evolution of the source-drain leakage current in an NMOS transistor in 130nm CMOS during a TID exposure.
- The TID peak (position and height) depends on the temperature, bias, and dose rate.
- Consequences for (unexpected) detector power consumption.



Evolution of the source-drain leakage current in an NMOS transistor in 130nm CMOS during a TID exposure. The position and amplitude of the leakage peak depends on the temperature, bias and dose rate.

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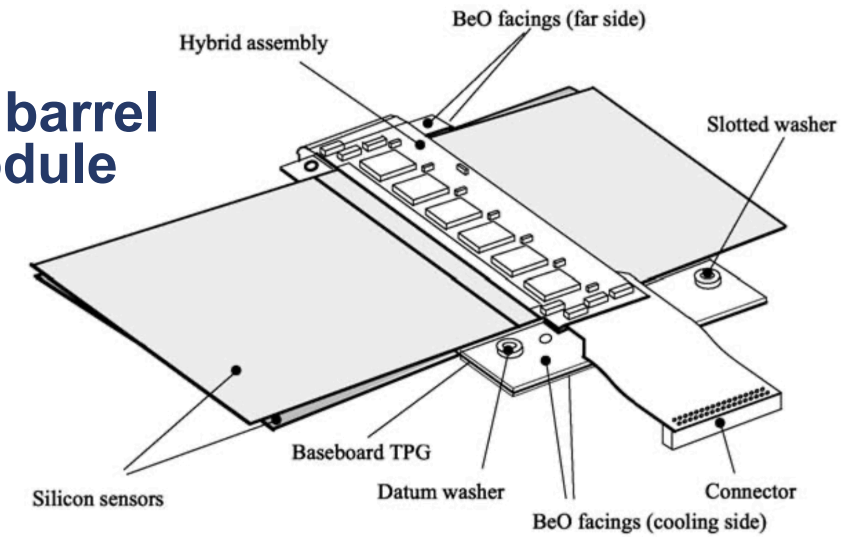
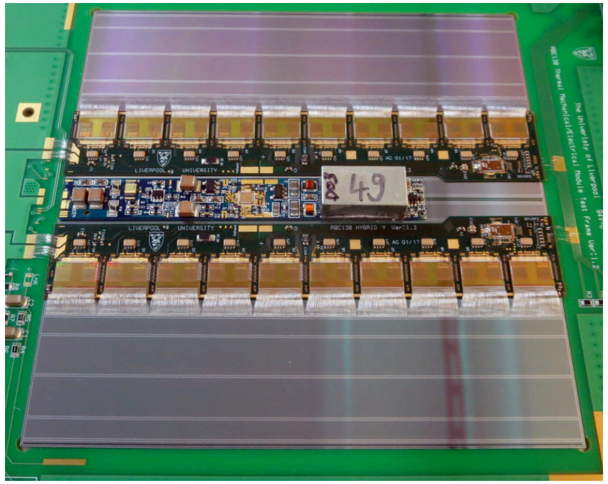
Qualifying detector designs for radiation resilience.

- Inner detector systems are designed to meet vertexing and tracking specifications defined by the experiment goals. E.g. space point precision; fast readout; good signal to noise; low noise occupancy; etc.
- However, the effects of radiation can impact design specifications, leading to: increased leakage currents and thermal runaway; decreases in charge collection and S/N; increases in depletion voltages and breakdown; Single Event Upsets and DAQ issues; mechanical degradation.
- How do we make sure the detector design is fit for purpose over the lifetime of the experiment?

SCT barrel module

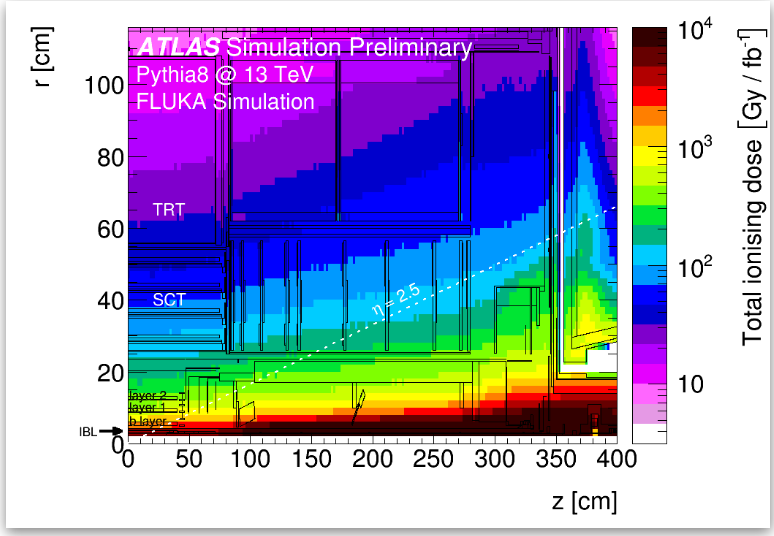


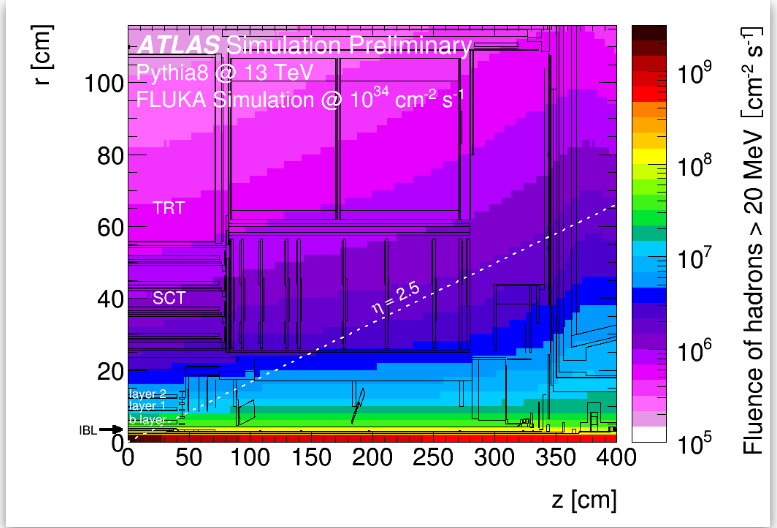
ITk barrel module



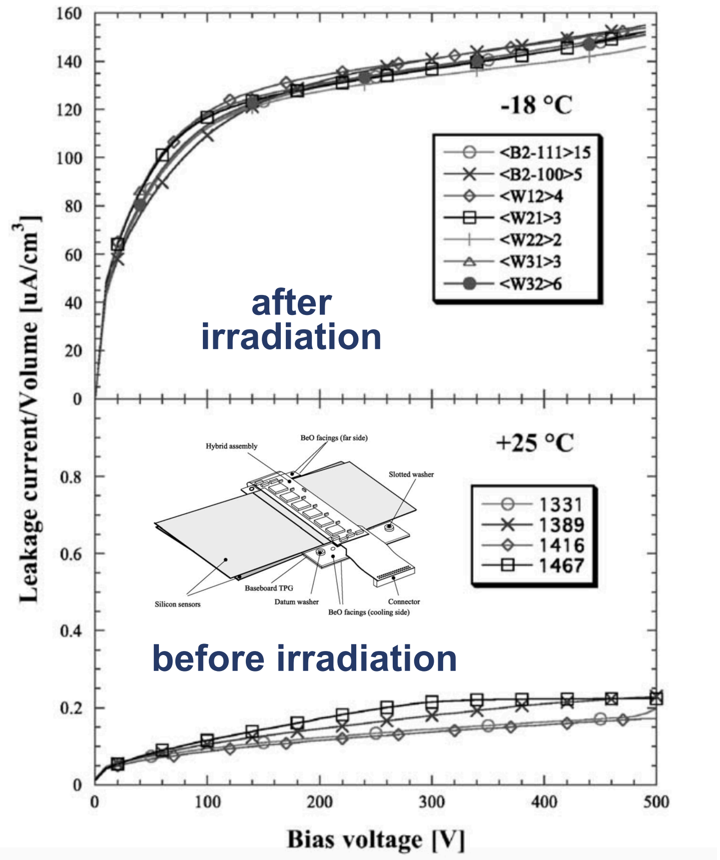
Qualifying detector designs for radiation resilience.

- For the SCT we simply took the simulated fluence and dose results, applied a best guess “safety factor”, and irradiated our devices in an appropriate test facility.
- For cumulative quantities such as total ionising dose (TID) or 1 MeV neutron equivalent fluence, the translation from simulation to test facility is straight forward. However have to take care with dose-rate effects.
- For Single Event Upsets (SEU) in electronics, studies have shown that rates can be estimated from the simulated hadron fluence > 20 MeV, and using proton or pion facilities > 60 MeV.





Qualifying detector designs for radiation resilience.



ATLAS SCT I-Vs before and after irradiation 3x10^{14} protons for different sensor shapes and crystal orientation.

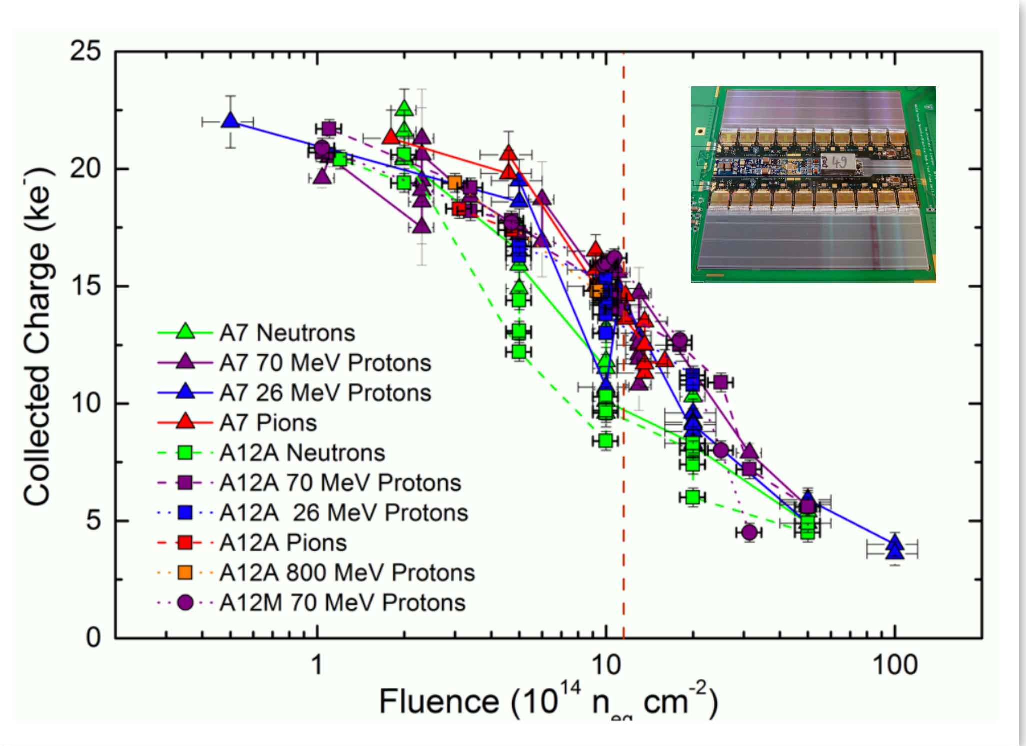
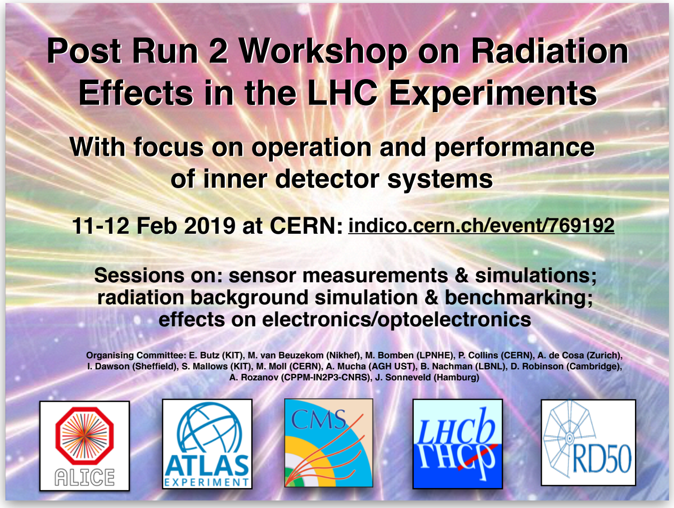


Figure 6.2: Collected signal charge at 500 V bias voltage for minimum ionising particles as a function of 1 MeV n_{eq}/cm^2 fluence for various types of particles [61]. The vertical dashed line indicates the maximal expected fluence within the ITk Strip Detector (incl. safety factor).

Qualifying detector designs for radiation resilience.

- For upgrade studies, we can now input our experiences from running at the LHC.
- In particular, by comparing simulation and model predictions with detector measurements (e.g. leakage currents) we can reevaluate the safety factor uncertainties (discussed in the next section), which has a big impact on cost.



Safety Factor and Testing Procedure Recommendations of the Radiation Effects Task Force

Approved by ATLAS Upgrade Steering Committee June 18, 2020

(ATLAS internal)

Prepared by:

G.Borghello, I. Dawson, F. Faccio, M. Huhtinen, S. Menke

RETF active members:

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† Co-chair
‡ Invited outside expert

CERN Yellow Reports: Monographs CERN-2021-XXX

Radiation effects in the LHC experiments

Impact on detector performance and operation

Editor: Ian Dawson, Queen Mary University of London

CERN Yellow Report (under review)

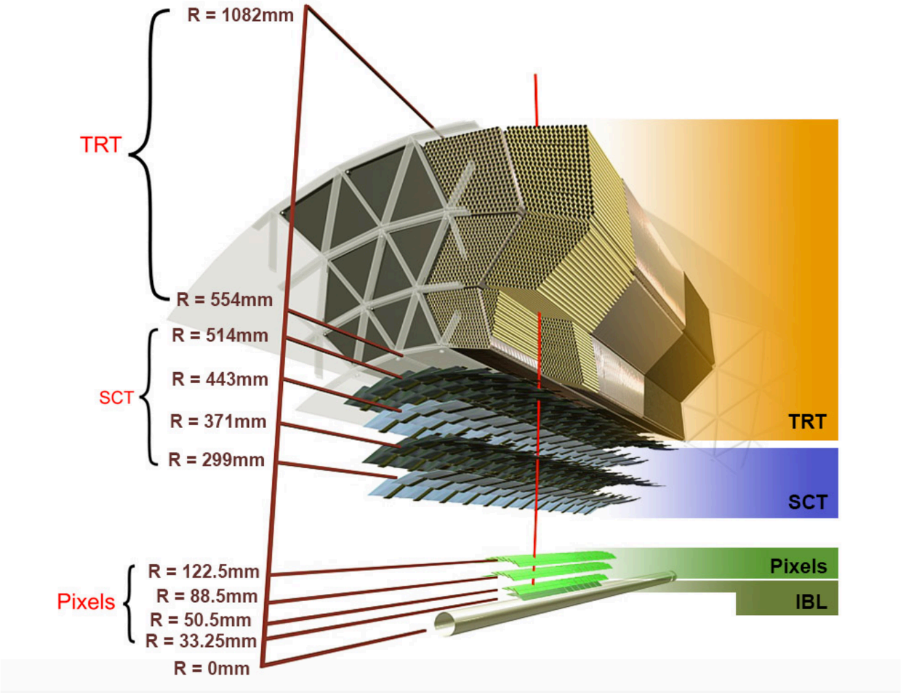
CERN

Radiation environment simulation at the LHC experiments and detector damage studies.

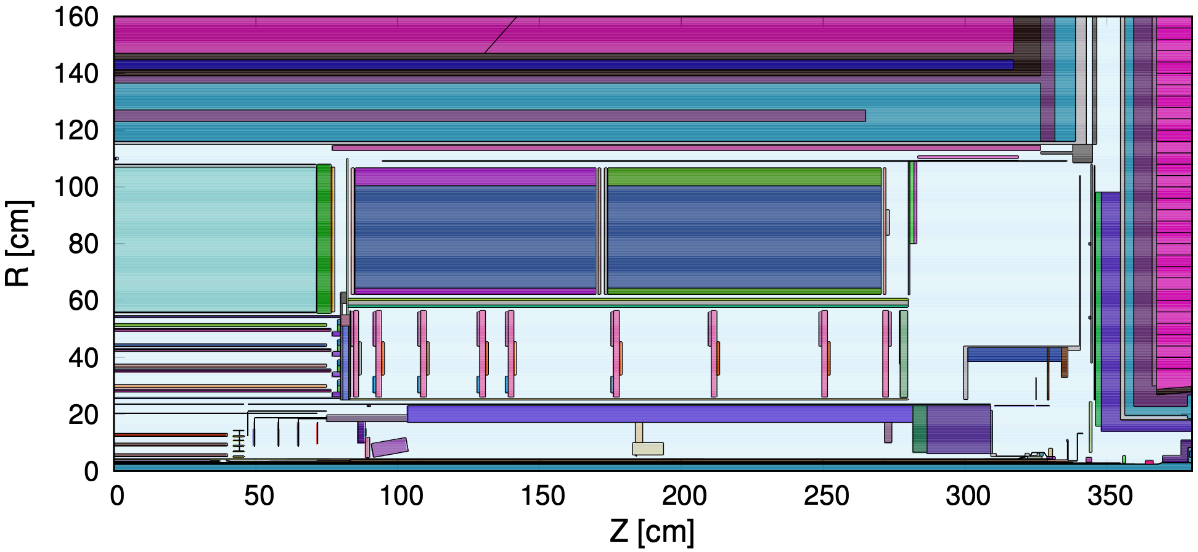
1. **Introduction:** The Large Hadron Collider at CERN.
2. **Simulating radiation environments?** Event generators. Transport of particles interacting with matter. FLUKA and GEANT4. Fluence and dose.
3. **Radiation damage effects:** Bulk displacement damage. Damage modelling. Charge interface effects. Single Event Effects.
4. **Qualifying detector designs for radiation resilience:** Linking test facility irradiations to real life applications. Radiation Hardness Assurance.
5. **Impact of radiation on ATLAS detector performance:** Radiation damage measurements in Runs 1 and 2 and comparisons with model predictions.
6. **Knowledge transfer to industry?** Synergy with aerospace and nuclear industries.

Detector measurements and comparisons with model predictions.

- We will focus on inner detector measurements, where the radiation backgrounds are most harsh due to proximity of the proton-proton collisions.



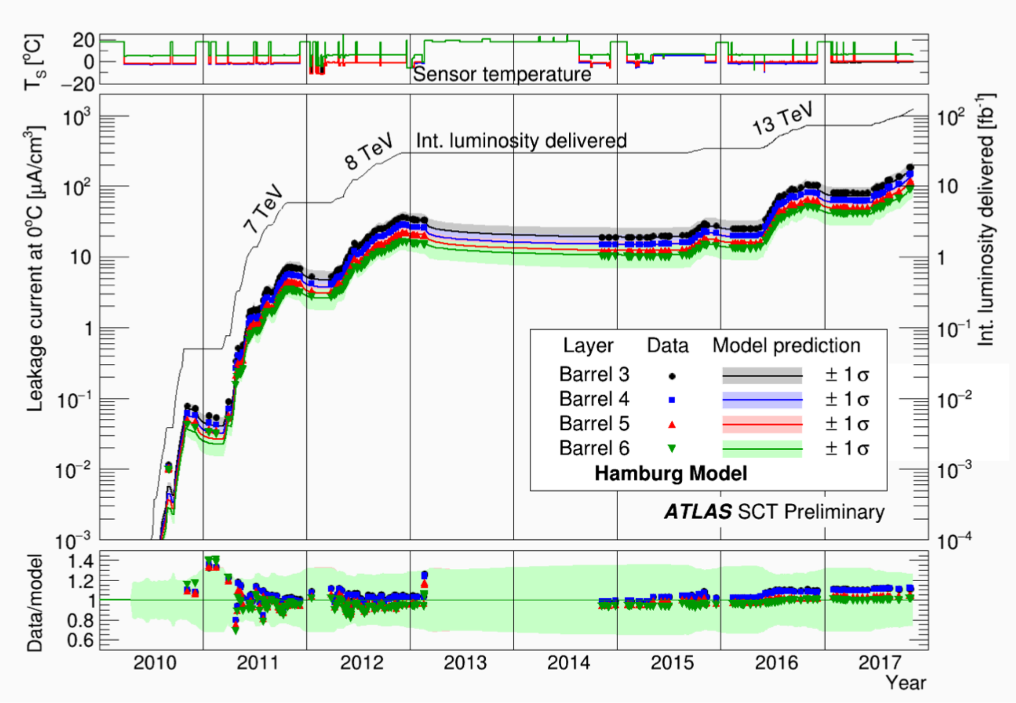
Schematic view of the ATLAS inner detector.

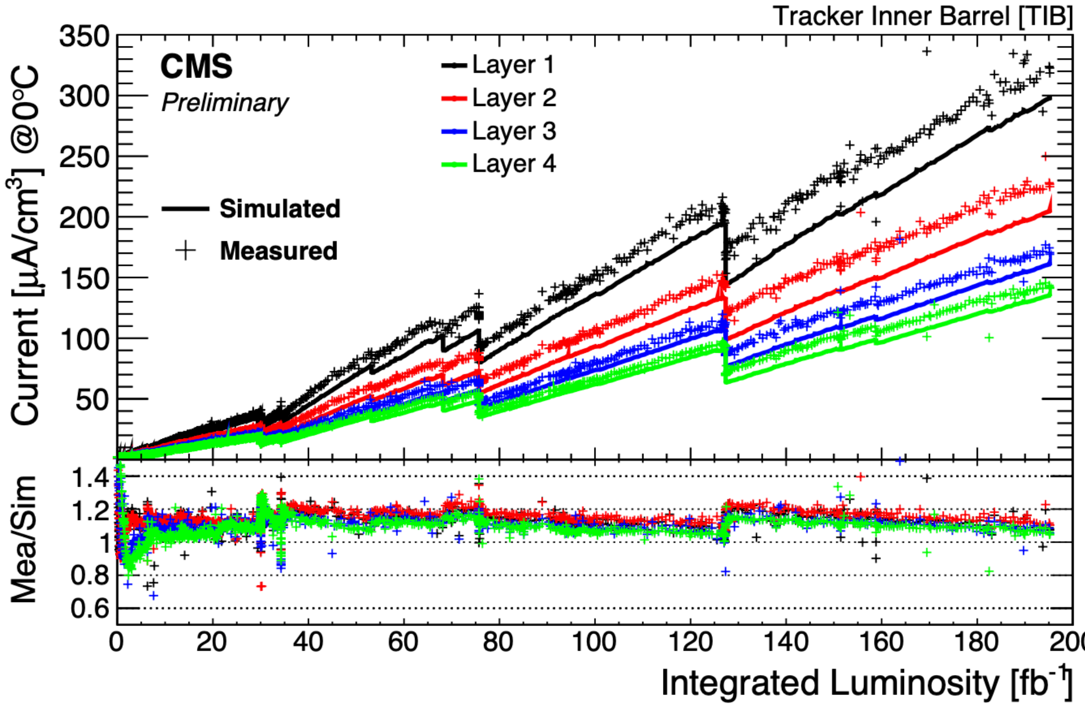


ATLAS ID geometry described in FLUKA.

Detector measurements and comparisons with model predictions.

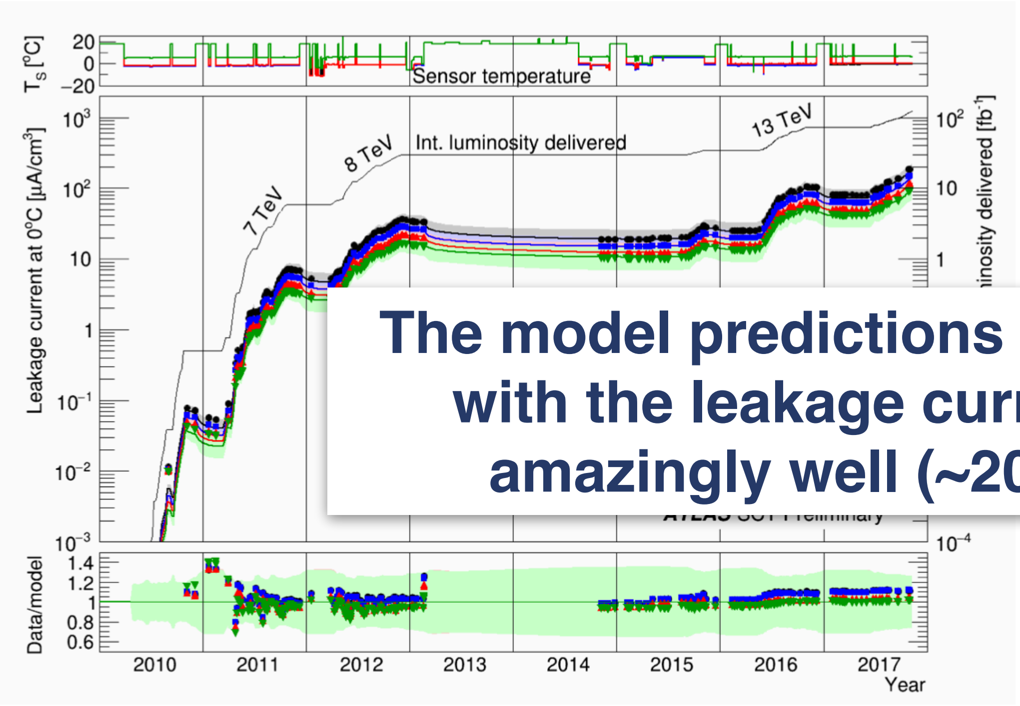
- First take a look at leakage current evolution in the silicon tracker systems.

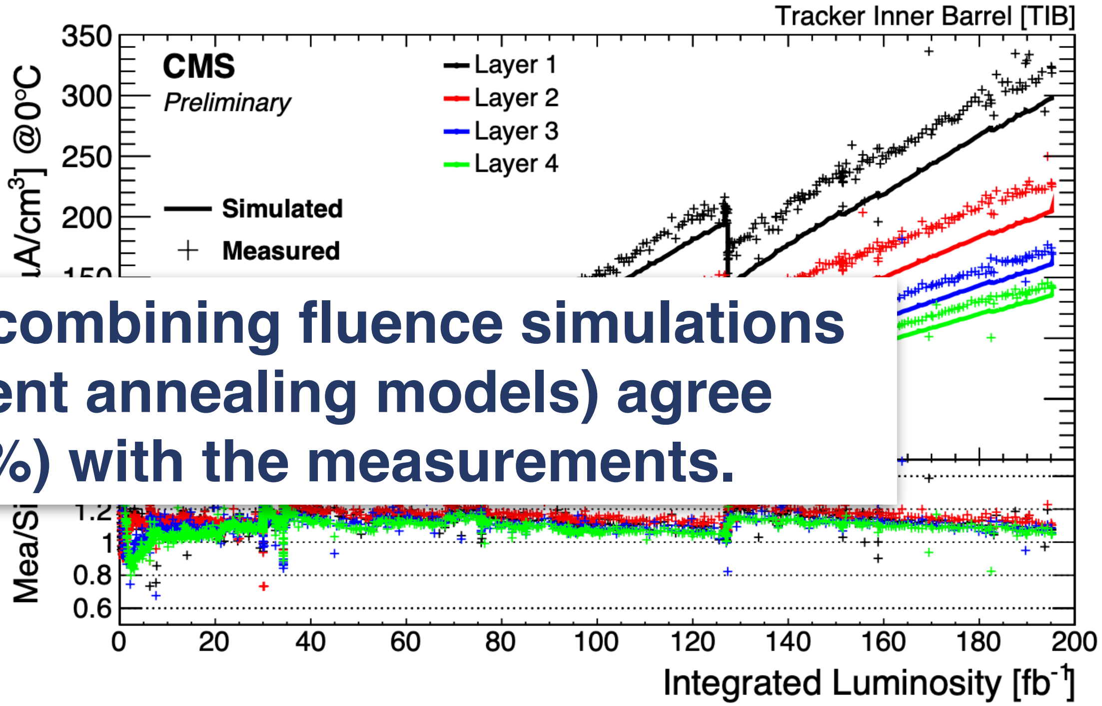




Detector measurements and comparisons with model predictions.

- **First take a look at leakage current evolution in the silicon tracker systems.**

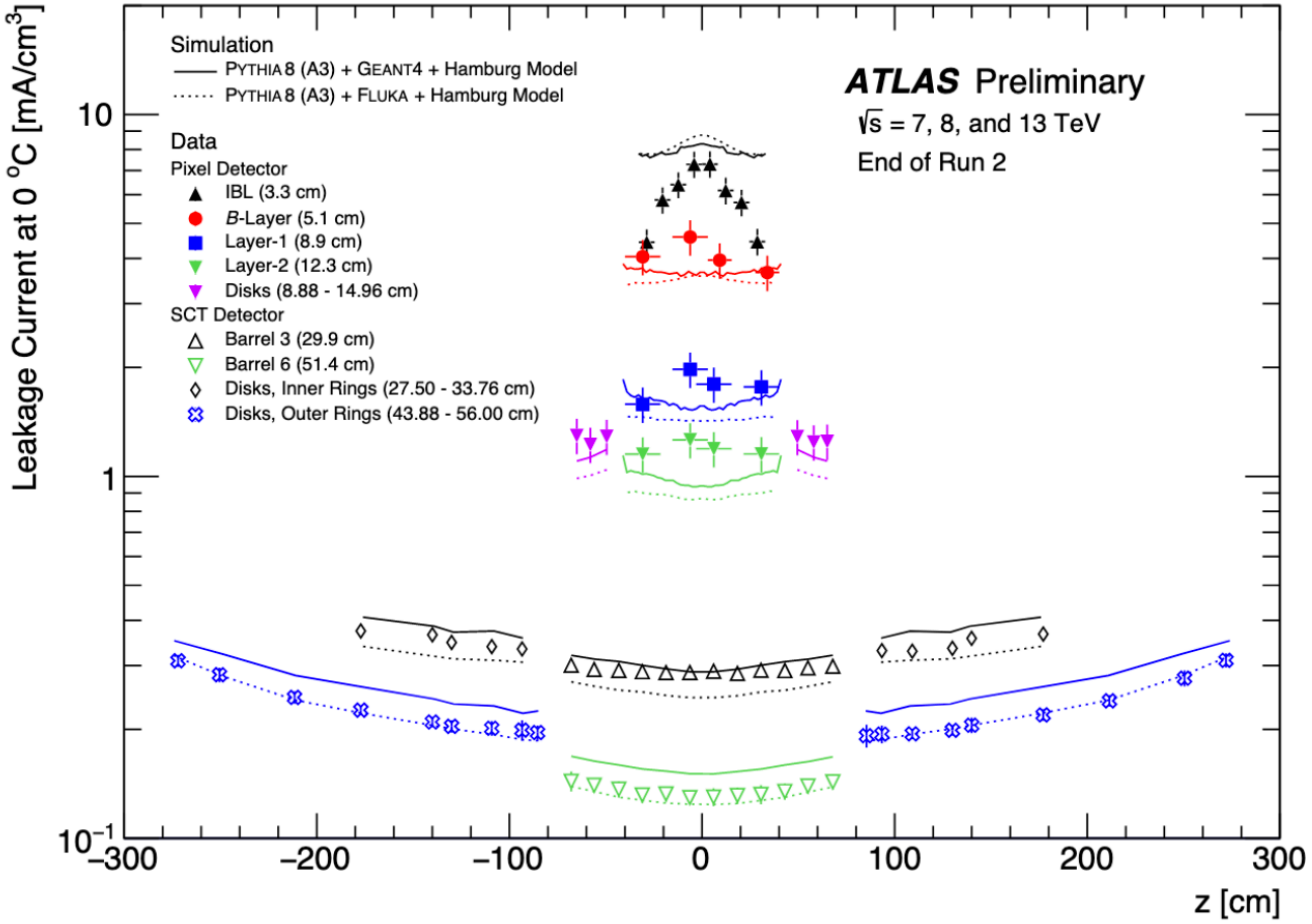




The model predictions (combining fluence simulations with the leakage current annealing models) agree amazingly well (~20%) with the measurements.

Detector measurements and comparisons with model predictions.

- What about the innermost (pixel) detector layers?
- On ATLAS we now have plots combining pixels and SCT, covering both barrel and endcap regimes.
- Compared to SCT, larger differences observed in pixels, with (unfortunately) simulations under predicting.
- The IBL z-dependence is a mystery! Measurement bias? NIEL violation? Incorrect minbias physics modelling in Pythia8?



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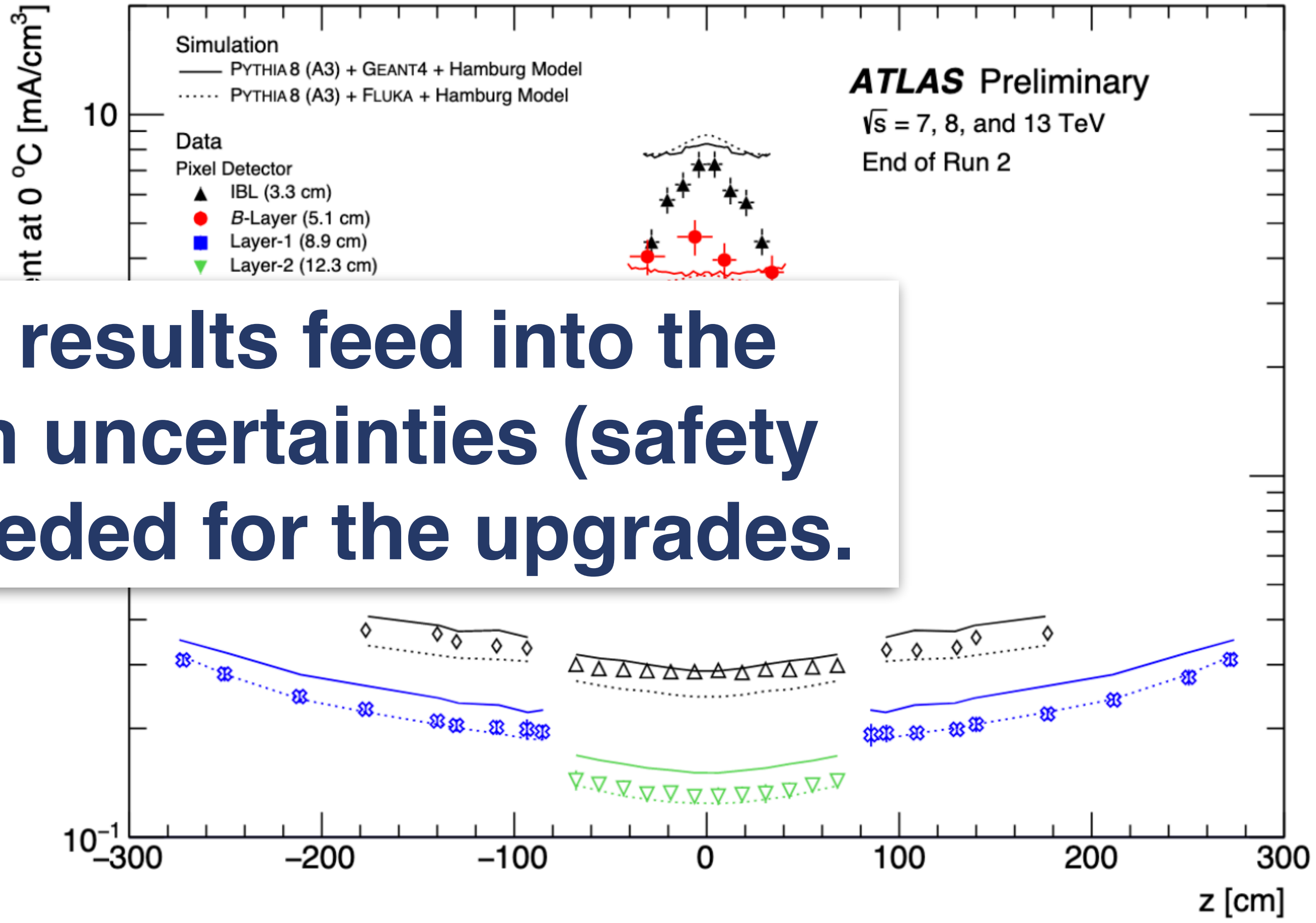
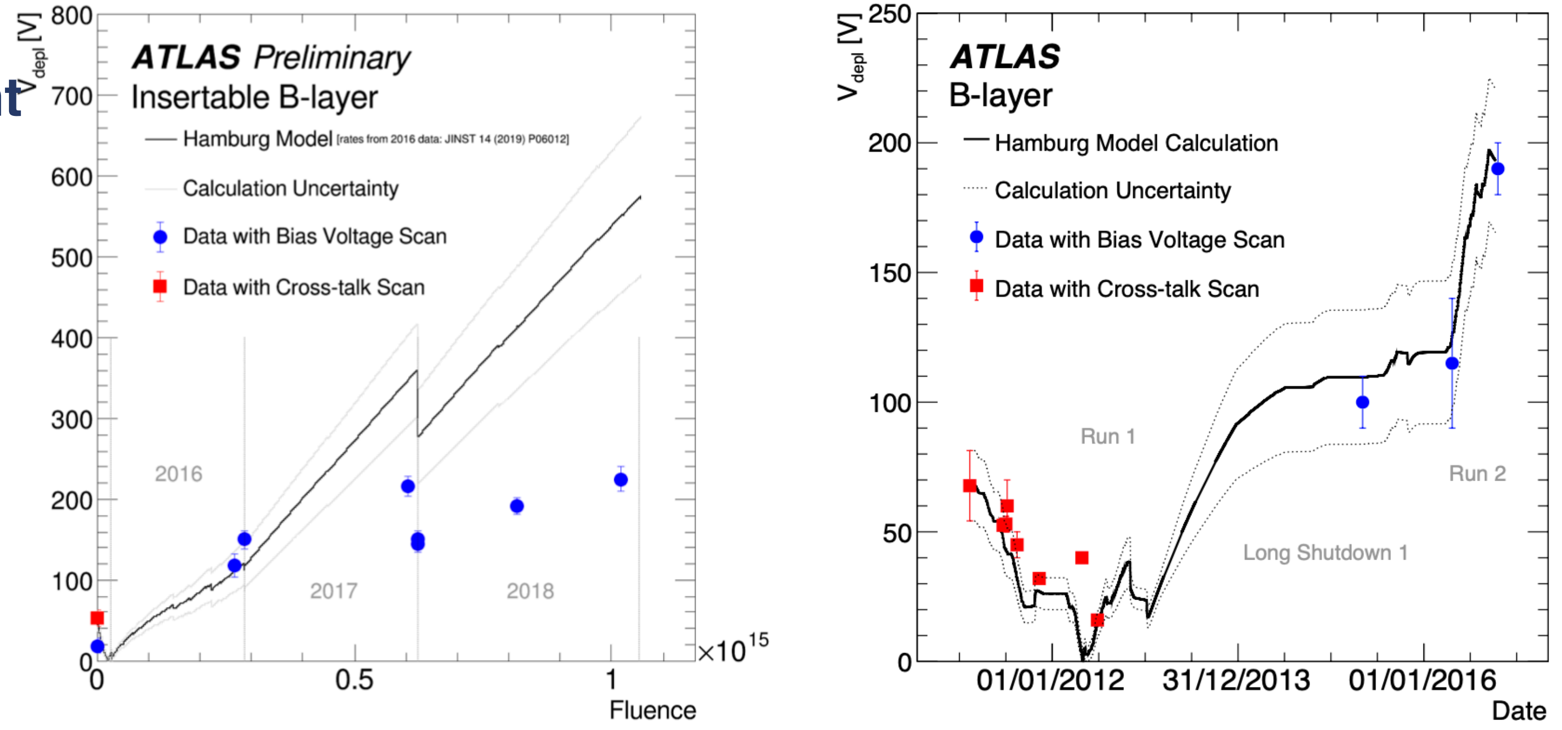


All these results feed into the simulation uncertainties (safety factors) needed for the upgrades.

Detector measurements and comparisons with model predictions.

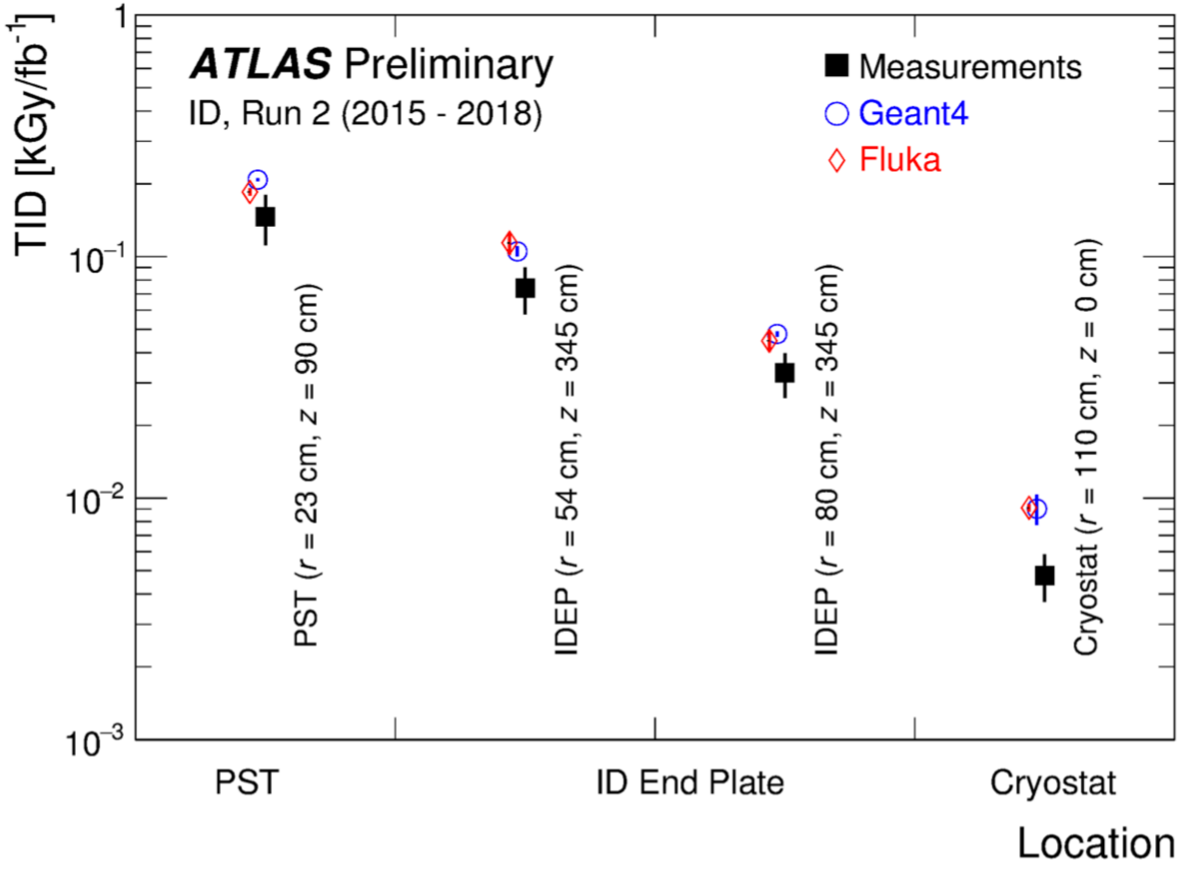
- **What about other important detector damage observables, such as increases in depletion voltages?**
- **A fully depleted sensor is important for signal extraction.**
- **Voltage supplies limited, and too high voltages can cause breakdown, so important to understand.**



Measurements and Hamburg model predictions for the ATLAS IBL (left) and B-layer (right). Circular points indicate measurements using bias voltage scan method, while square points correspond to cross-talk scans.

Detector measurements and comparisons with model predictions.

- Unfortunately the detector systems cannot measure ionising dose, for this we have “Radmon” monitors.
- Once again, agreement between simulations and measurements quite good.
- More important, better that the simulations overestimate than underestimate.



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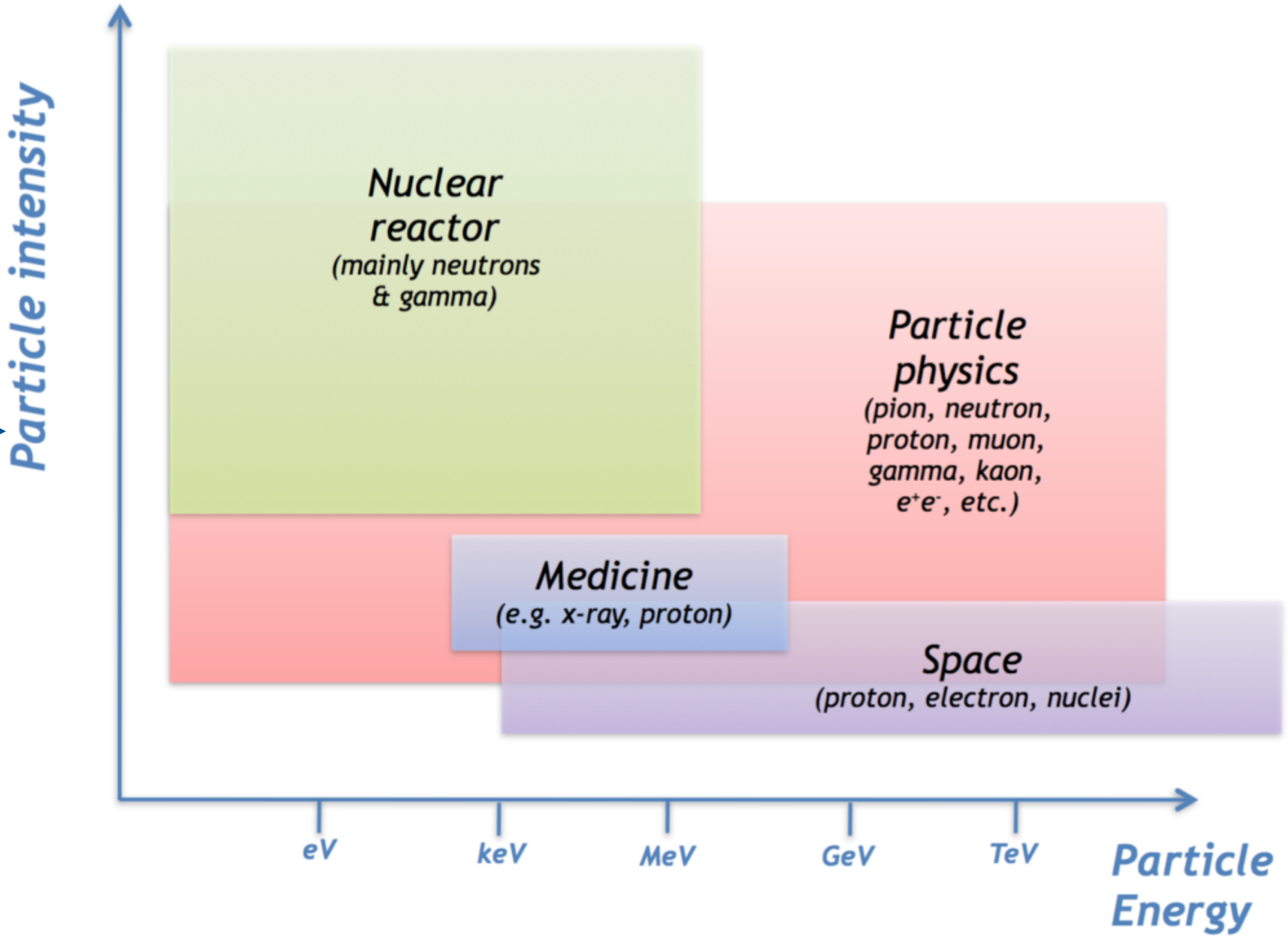
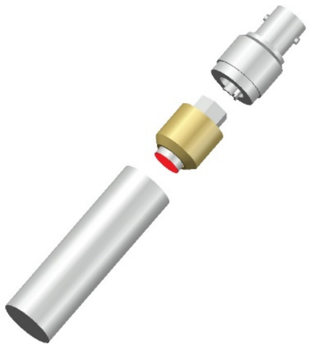
Synergy between industries?

- In terms of radiation simulation and testing, there is strong overlap between what we do in collider experiments and the aerospace and nuclear industries.
- For example, we've used FLUKA/ GEANT4 for simulation radiation effects in all these research fields.
- Similarly, radiation quantities such as ionising-dose, 1 MeV neutron equivalent flux, etc., are used across these sectors. Therefore the same irradiation test facilities can be used.



Example of partnerships with industry SMEs to develop radiation resilient ultrasound transducers (UT) for non destructive testing in nuclear applications.



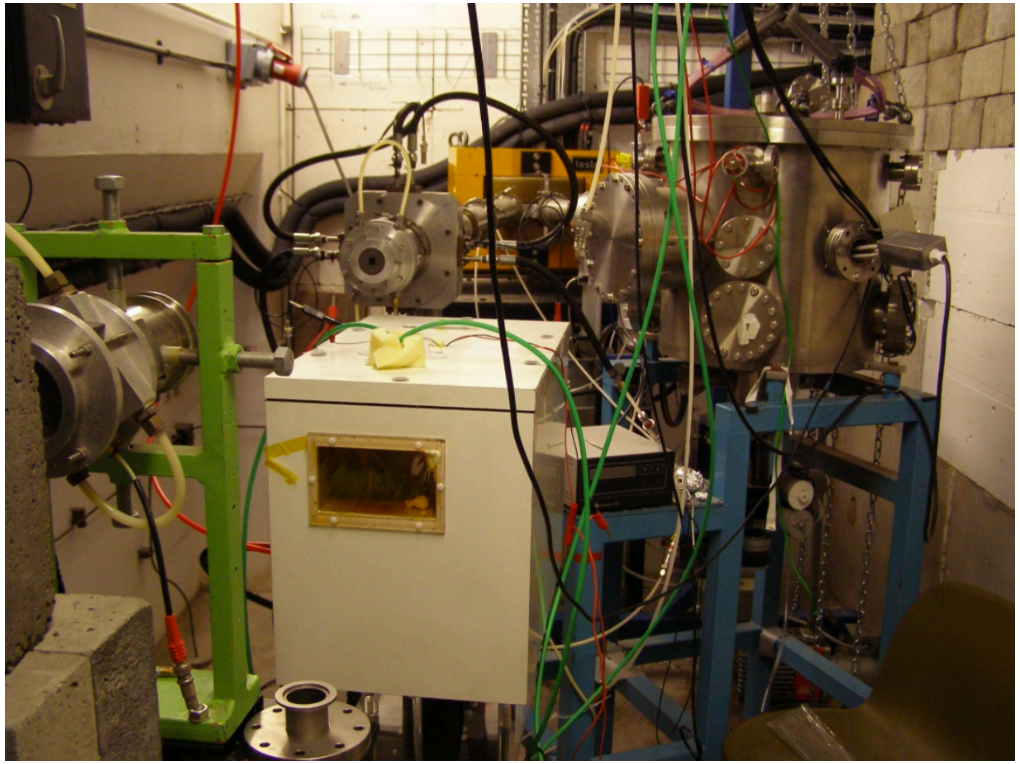
PRECISION ACOUSTICS

Investigate piezopolymer (PVDF) ultrasound transducers for radioactive waste monitoring. Understanding gamma response crucial. PVDF sensor material of interest for high frequency/resolution imaging applications.

ionix ADVANCED TECHNOLOGIES

Piezoceramic based ultrasound transducers for monitoring extreme environment applications, such as inside nuclear reactors. Evaluating both neutron and

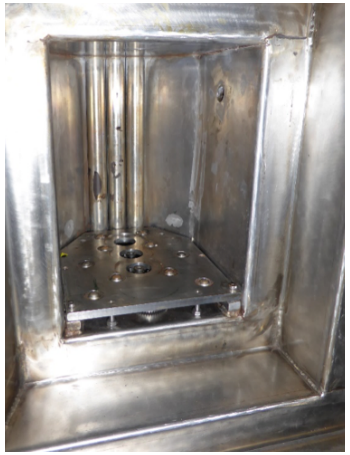
Once again simulation provides the link between the real life radiation environment and the test facilities.



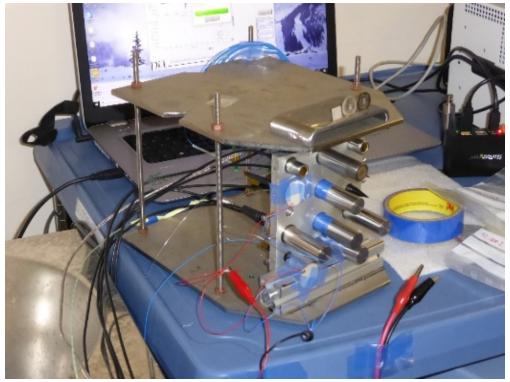
High flux 27 MeV protons for ionising dose and bulk material damage.

Nuclear reactor for neutron and gammas damage studies.

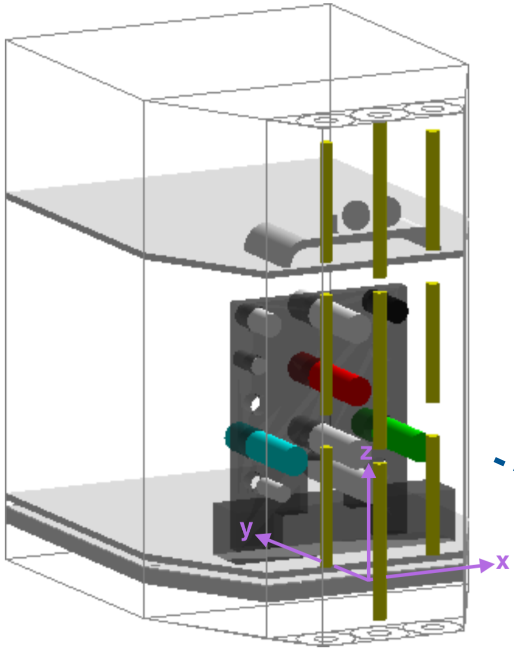
Gamma irradiations and simulations.



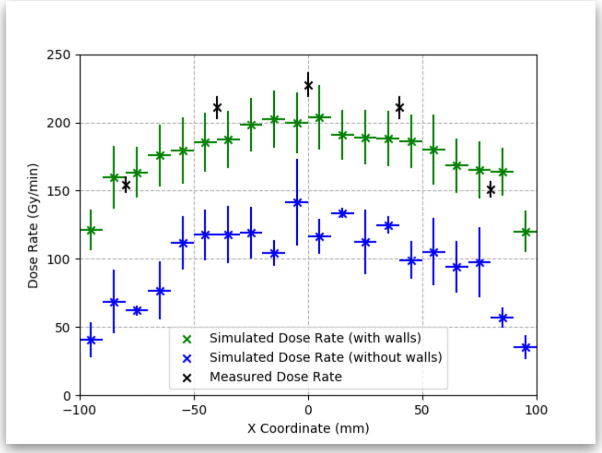
Dalton Co-60 gamma irradiation chamber.



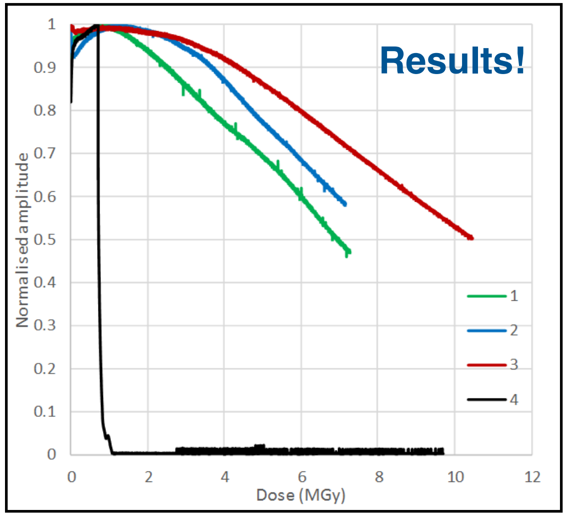
UT probes mounted in rack.



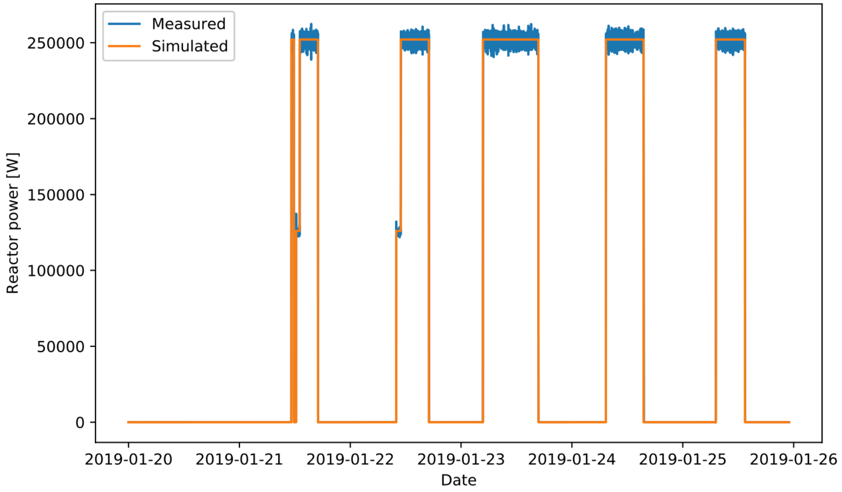
To understand the dose profiles inside the probes, we modelled in GEANT4 the irradiation chamber, Co60 rods, and UT probes.



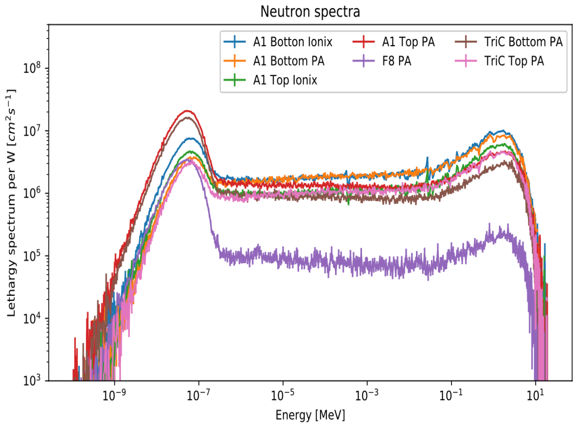
Benchmarking/calibration of simulations with data.



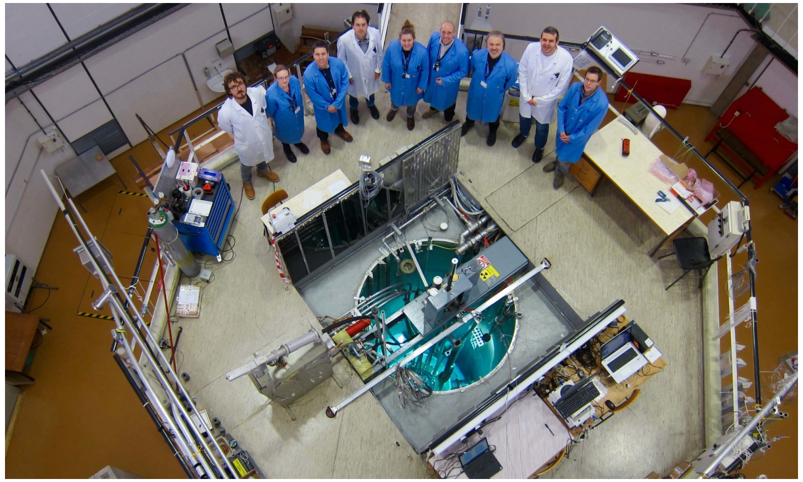
Neutron irradiations and simulations.

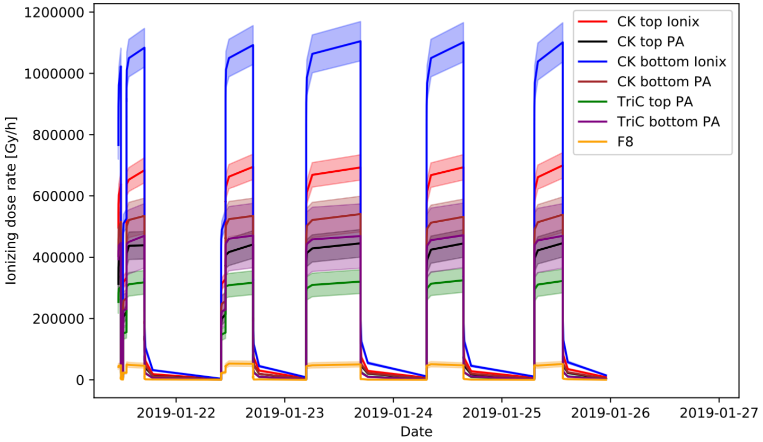


Reactor power over 5 days



Neutron energy spectra (MCNP6) different locations.





Total ionising dose different locations

b. TRIGA reactor (gamma and neutron)

Results!

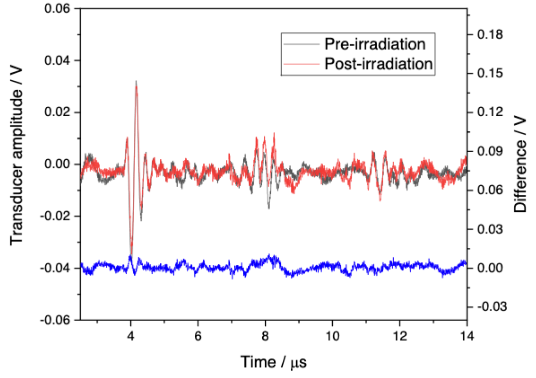
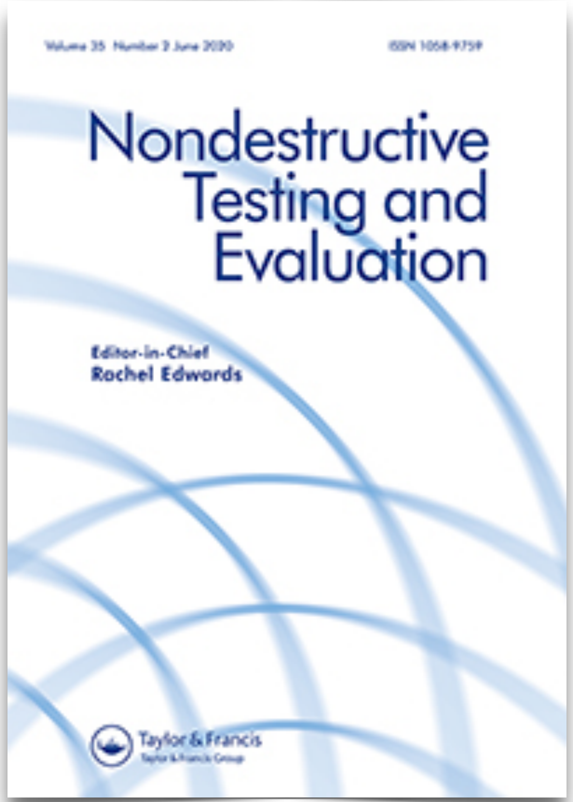


Figure 5 – Initial (grey) and final (red) A-scans after 100 hrs of irradiation in the TRIGA reactor, with difference plot (blue) for a representative sensor. Total dose recorded was 11 MGy gamma, and integrated neutron flux 2.6 x10[18] n.cm[-2].

Outcome of project?




TECHNICAL DATA SHEET

PRECISION ACOUSTICS

Innovate UK
Technology Strategy Board

Radiation resilient ultrasonic transducers

Designed for ambient temperature inspection and NDT applications in high radiation environments, Precision Acoustics' 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 5-20 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.


HotSense™ monitoring in the nuclear environment

for ***Wall Thickness*** *and* ***Gas Void*** *measurements*

ionix
ADVANCED TECHNOLOGIES

1. Scope of this Technical Note

Ultrasonic testing (UT) transducers are used in the nuclear non-destructive testing (NDT) industry for various applications including wall thickness integrity monitoring and gas void locating and sizing. Traditionally, these measurements are made manually by inspectors who must physically hold the UT transducer onto the measurement location, often in hazardous environments including ionising radiation, high temperatures and working at height or in confined spaces. Installed, fixed point, UT transducers can be used with either automated remote monitoring systems or with cables which extend to safe zones. Fixed UT transducers promote a safer and more efficient maintenance program with the following key areas of benefit:

1. **Increase safety** by reducing exposure of employees to hazardous environments
2. **Minimise the dose** of radiation staff incur when performing their duties by reducing the time spent at the location
3. **Reducing the total time** required to collect measurements by removing the challenges of restricted access ie. no need for rope access or scaffolding

Radiation endurance of commercially available UT sensors/transducer is limited to cumulative doses of only 1 to 2 MGy, even for models branded as radiation resistant. Severe operational difficulties can occur due to unexpected UT transducer failure and recurrent sensor replacement is both time consuming and expensive. Additionally, to successfully monitor whilst the plant is in-service, requires resilience to high operating temperatures (up to 350 °C).

The Ionix HotSense™ ultrasonic transducer platform is designed for operation in these extreme environments, with continuous operation viable up to 380 °C and beyond. Previous testing for the radiation resilience of the Ionix HPZ piezoelectric material alone, demonstrated no significant degradation upon a cumulative gamma dose of 11 MGy.

Here, the suitability of the HotSense™ transducers for monitoring in nuclear environments is shown, with exposure to both gamma and neutron radiation without any observable performance degradation.

Highlights:

- *HotSense™ transducers are proven to operate continuously within nuclear plant environments for fixed point monitoring of* ***asset integrity*** *and* ***gas void measurement****.*
- *Assets can be monitored in-service without the need to shut down, access or isolation.*
- *No observed performance degradation after exposure to 10.9 MGy of gamma irradiation.*
- *No observed performance degradation after exposure to 11 MGy of gamma and $2.6x10^{18}$ c $^{-2}$ neutron fluence.*

Publication (Vol 35, Issue 2, 2020) and presentation at Advanced GEANT4 workshop.

Companies now advertising their radiation resilient products. Any lessons learned? SMEs have much to offer the aerospace and nuclear industries, but need expert support to navigate radiation hardness assurance and test facility usage.

Questions?

Back up slides

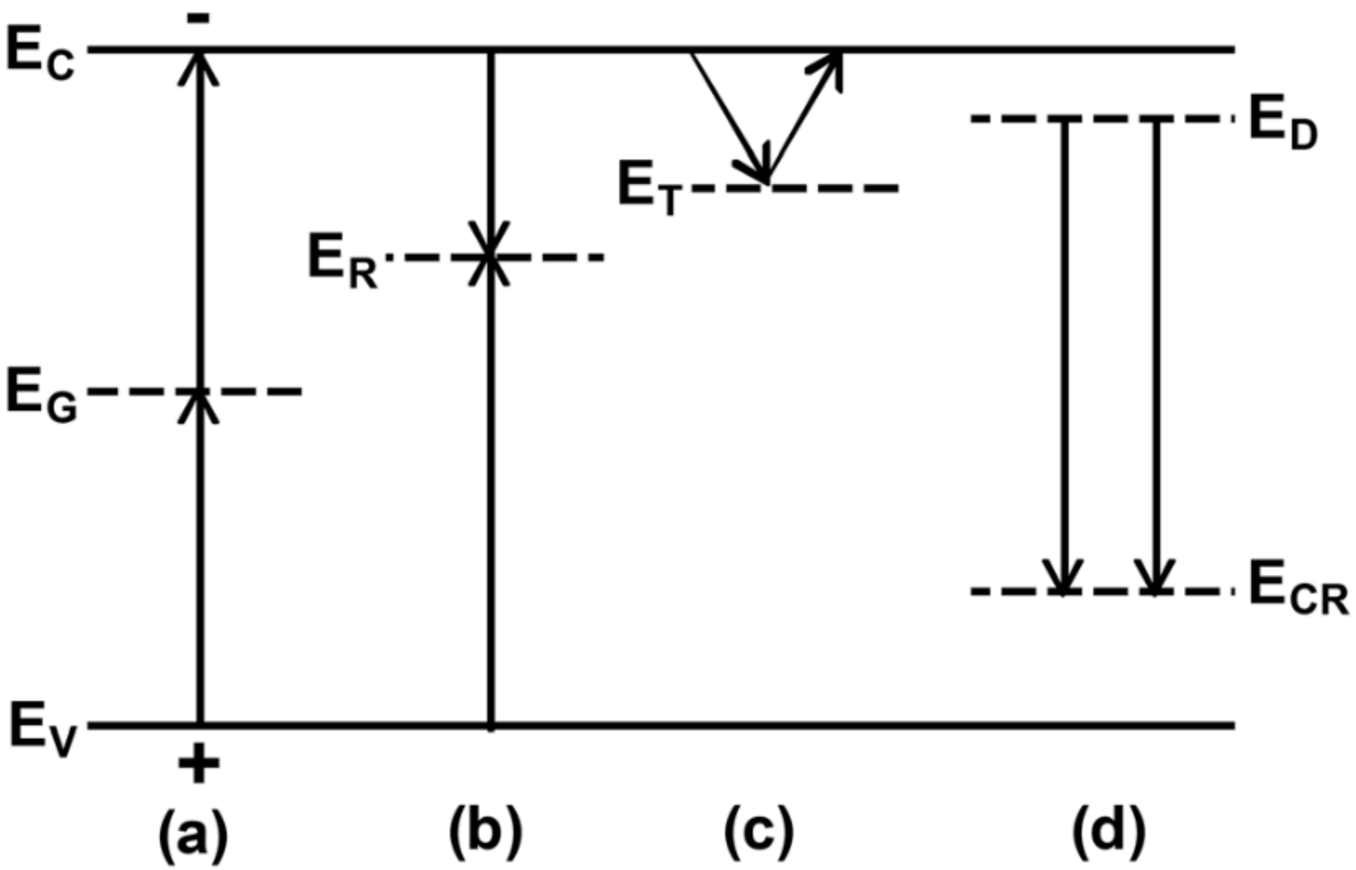
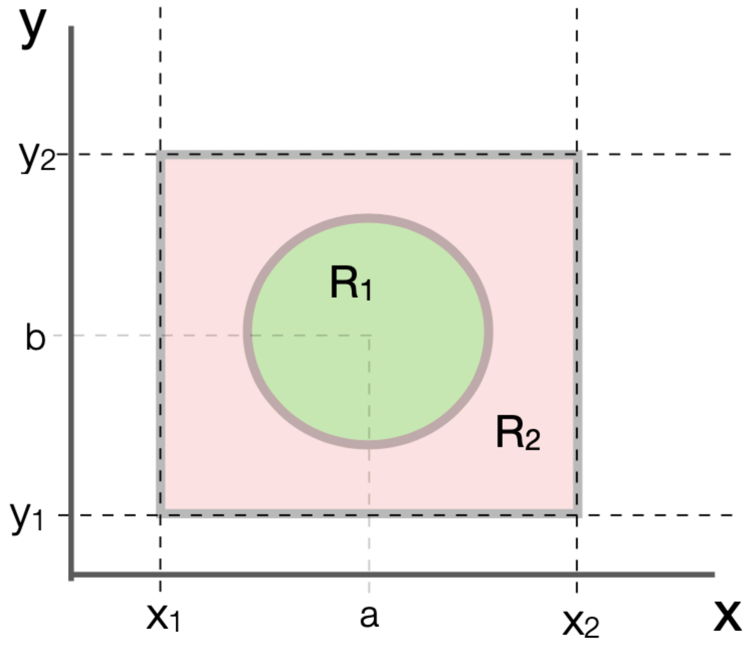


Illustration of four effects of displacement damage due to energy levels introduced in the bandgap.: a) increased therm generation of carriers; b) increased carrier recombination; c) increased temporary trapping; d) reduction in majority-carrier concentration.

Describing geometries and tracking particles.

- Different methods to describe 3D geometry, e.g. FLUKA and MCNP use ***Combinatorial Geometry***, which combine the bodies (defined by surfaces) into regions using boolean operations (union, subtraction, etc.)

- Consider for example very simple 2D geometry, circle inside a square, and define two regions, which can be assigned different properties (e.g. material type, density)



- Define regions as:

R_1: $[(x-a)^2 + (y-b)^2 < r^2]$

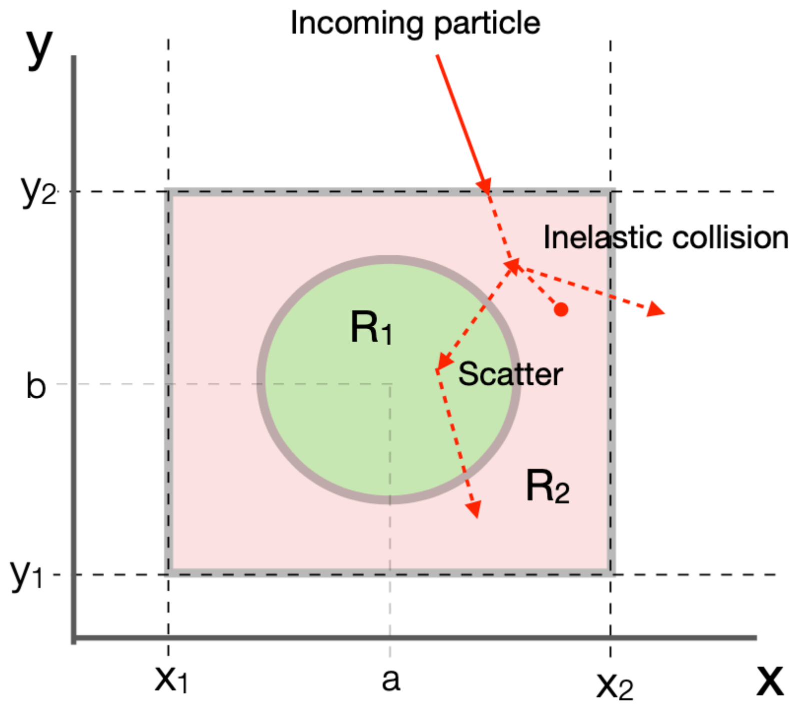
R_2: $[(x-a)^2 + (y-b)^2 > r^2]$ **&** $[x > x_1]$ **&** $[x < x_2]$ **&** $[y > y_1]$ **&** $[y < y_2]$

Describing geometries and tracking particles.

- For problems where the **mean free path** between interactions is greater than geometry dimensions, fast determination of the boundary between regions becomes crucial.

- The mean free path is determined from all the possible physics processes implemented in the MC.

- Different MCs have different algorithms for accurately determining the boundary location and decide if an interaction will occur before the boundary is reached.



Simple example of FLUKA input file

```
TITLE
Target studies
*************************** PHYSICS SETTINGS *********************************
DEFAULTS                                                              PRECISIO
*
BEAM           -10.0                                                  PROTON
BEAMPOS          0.0       0.0      -0.1       0.0       0.0
*
****************** GEOMETRY & MATERIAL DESCRIPTION *************************
GEOBEGIN                            21.0                              COMBINAT
target300.geo
GEOEND
MATERIAL        14.0    28.088     2.328      14.0                    SILICON
* silicon disc
ASSIGNMA        14.0       2.0
* blackhole
ASSIGNMA         1.0       1.0
* dummy vacuum regions
ASSIGNMA         2.0       3.0       4.0
*
********************* PARTICLE TRANSPORT CUTS ******************************
PART-THR     -1.0E-5       1.0      16.0       0.0       0.0       1.0
EMFCUT       -1.0E-6    1.0E-6       0.0       1.0      14.0          PROD-CUT
*
*********************** OUTPUT AND SCORING *********************************
SCORE          208.0     211.0
USRBIN          12.0     211.0      91.0       2.0       0.0       0.0 en211
USRBIN           2.0       0.0       0.0       1.0       0.0       0.0 &
USRBIN          12.0     236.0      91.0       2.0       0.0       0.0 1MeV
USRBIN           2.0       0.0       0.0       1.0       0.0       0.0 &
*USRBDX          1.0      15.0      36.0       3.0       2.0       1.0 mySiDam
*
*********************** START SIMULATION ***********************************
START         1000.0
STOP
```

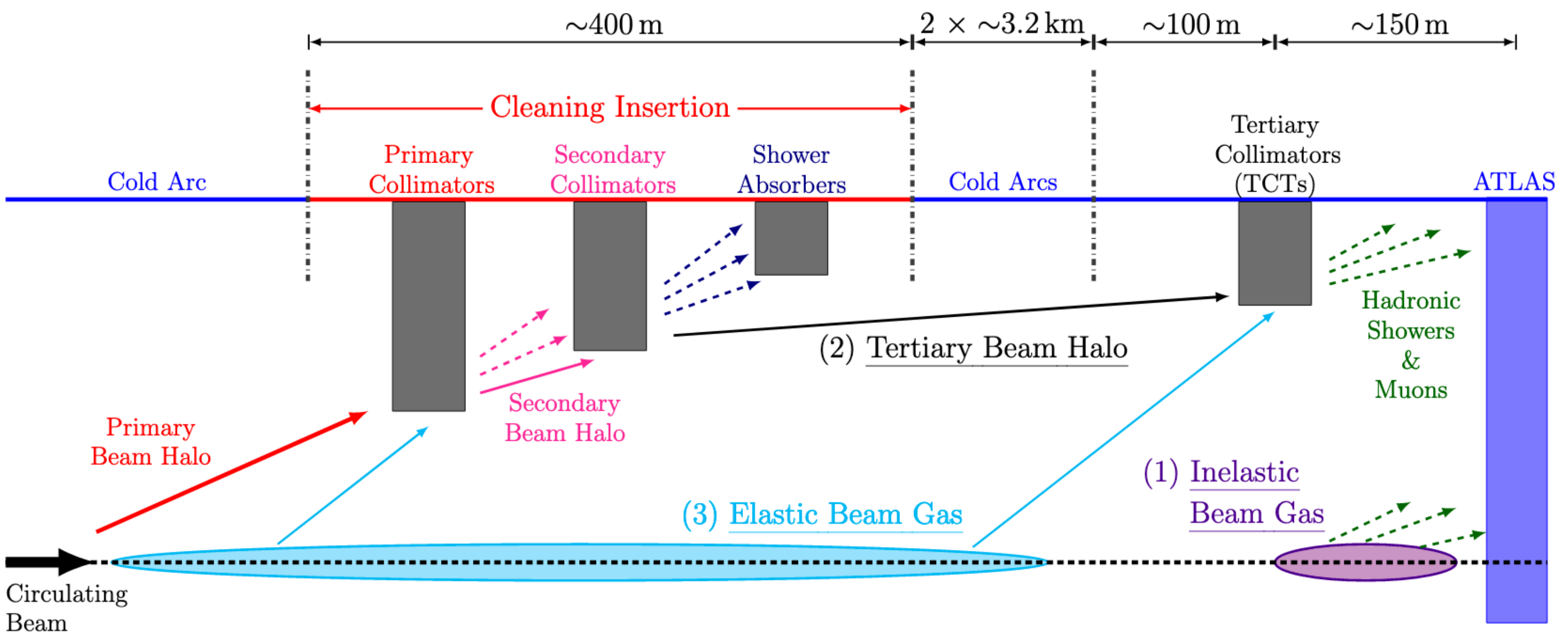
```
    0    0          silicon detector geometry
*
* X-axis up, Y-axis right, Z-axis into the page.
*
********************** Body definitions *********************************
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....
  RPP    1   -1000.0    1000.0   -1000.0    1000.0   -1000.0    1000.0
  ZCC    2       0.0       0.0       1.0
  XYP    3      -1.0
  XYP    4       0.0
  XYP    5      0.03
  XYP    6       1.0
*
  END
*
********************** Region definitions *******************************
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....
* Blackhole
  001      OR   +1     -2     -3     +6OR   +1     +3OR   +1     -6
* silicon disc
  002           +2     -4     +5
* vacuum region upstream of si-disc
  003           +2     -3     +4
* vacuum region downstream of si-disc
  004           +2     -5     +6
*
  END
```

Simple target cylinder geometry

Queen Mary University of London

Simulating radiation environments.

- **What about machine backgrounds? (E.g. beam-gas, beam losses).**

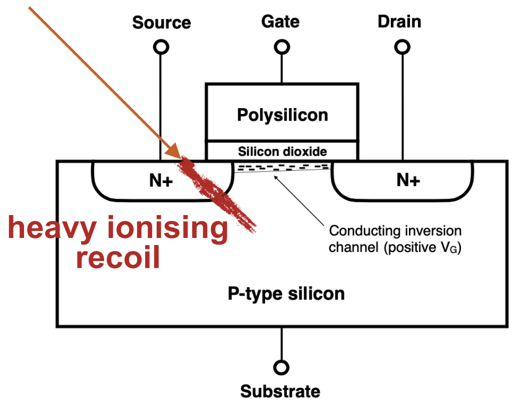


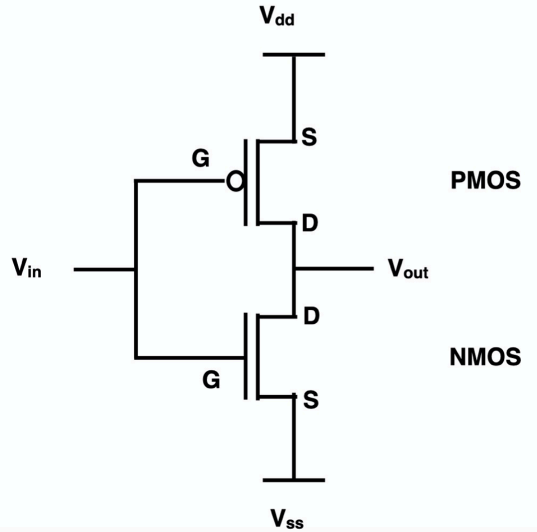
- **At high luminosity, studies show machine backgrounds have less impact on LHC experiments compared to pp collisions, but still important to understand for some backgrounds in physics analyses (similar to cosmics).**

M. Aaboud *et al* 2018 *JINST* **13**

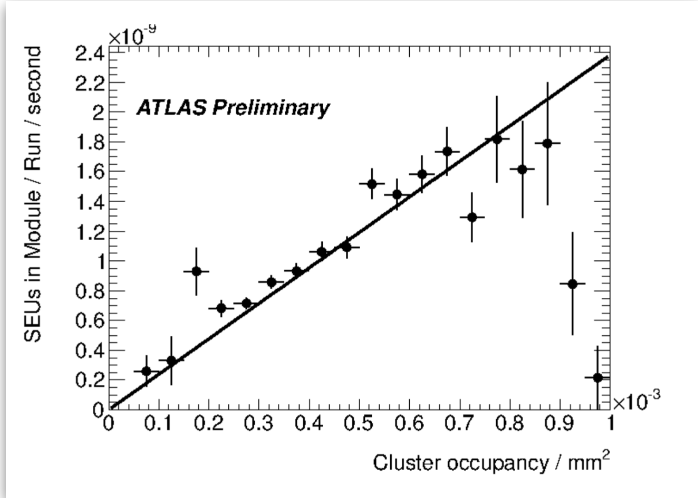
Single Event Effects

- When an ionising particle deposits sufficient charge in a sensitive node, its normal function can be disrupted.
- A simple example is a single event upset (SEU) when a ’1’ is changed to a ’0’ (or vice-versa) in a logic circuit or memory cell.
- The SEU sensitivity of a chip to radiation is measured in an appropriate irradiation facility (e.g. protons > 60MeV) and a cross-section is obtained.
- At the LHC this cross-section is combined with the simulated hadron fluence rate > 20 MeV to predict the rate of SEEs during operation.
- To avoid SEE either design special circuits or mitigate.



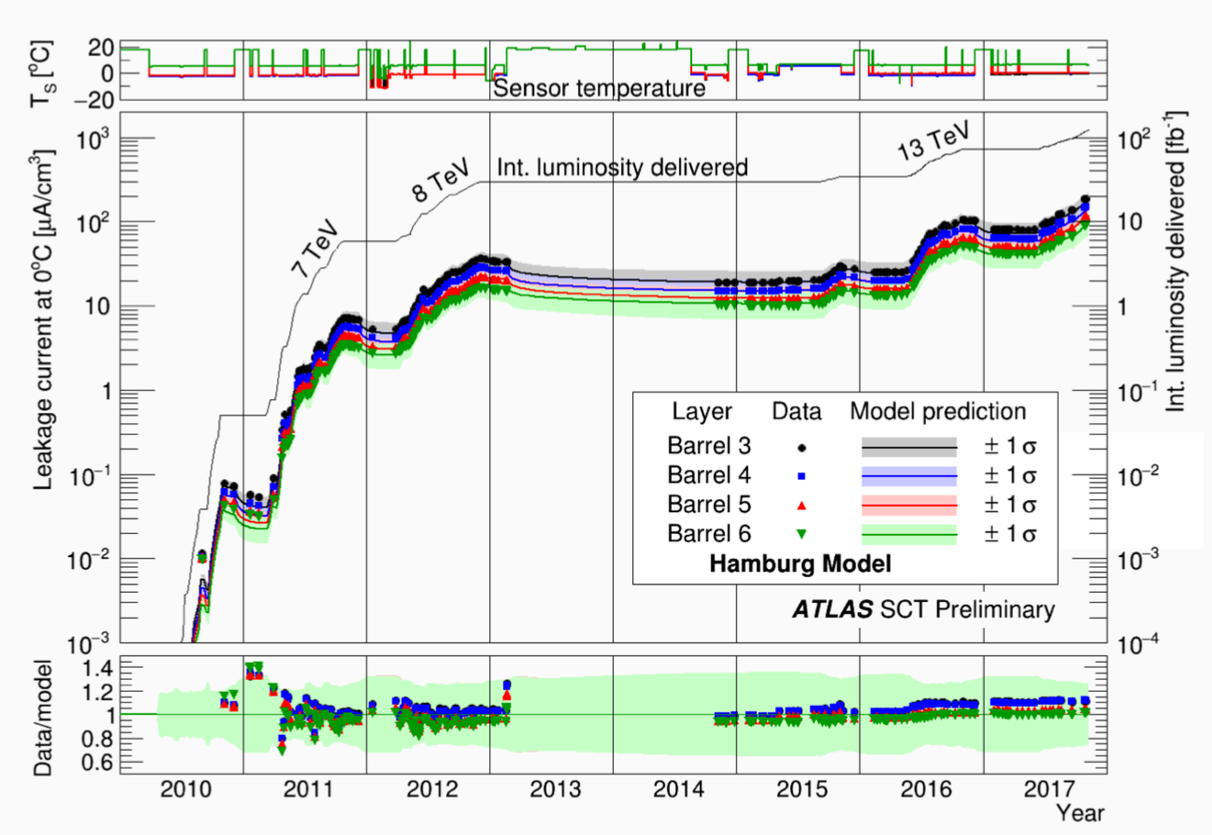


(Left) NMOS transistor with N-type implants in a P-type body. A positive gate voltage induces the a conduction n-channel at the SiO_2 interface where current can flow between source and drain. (Right) Combination NMOS and PMOS to make a CMOS inverter.



Example SEU rate in ATLAS SCT front-end ASIC DAC registers versus module occupancy (which is proportional to beam luminosity).

Displacement damage



- **We can use this NIEL scaling and parameterise our understanding of annealing to develop predictive models, such as the Hamburg leakage current model.**
- **By including also the simulated 1 MeV neutron fluence, we can now predict performance.**

(n time intervals)

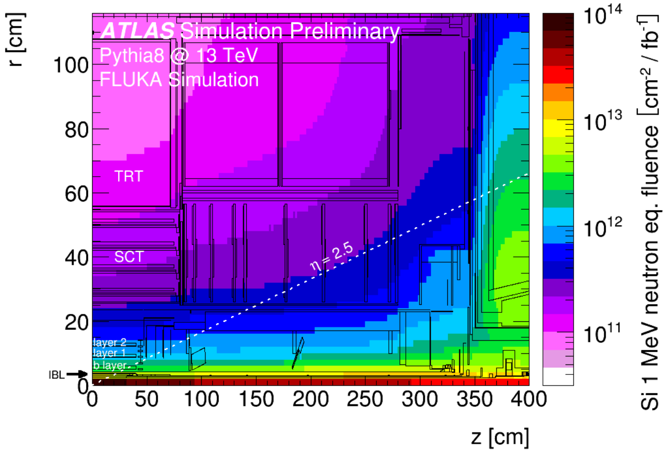
$$I_{\text{leak}} = (\Phi/L_{\text{int}}) \cdot \sum_{i=1}^{n} V_i \cdot L_{\text{int},i} \cdot \left[\alpha_I \exp\left(-\sum_{j=i}^{n} \frac{t_j}{\tau(T_j)}\right) + \alpha_0^* - \beta \log\left(\sum_{j=i}^{n} \frac{\Theta(T_j)\cdot t_j}{t_0}\right)\right]$$

$$I_{\text{leak}}(T_R) = I_{\text{leak}}(T) \left(\frac{T_R}{T}\right)^2 \exp\left[-\frac{E_{\text{eff}}}{2k_B}\left(\frac{1}{T_R} - \frac{1}{T}\right)\right]$$

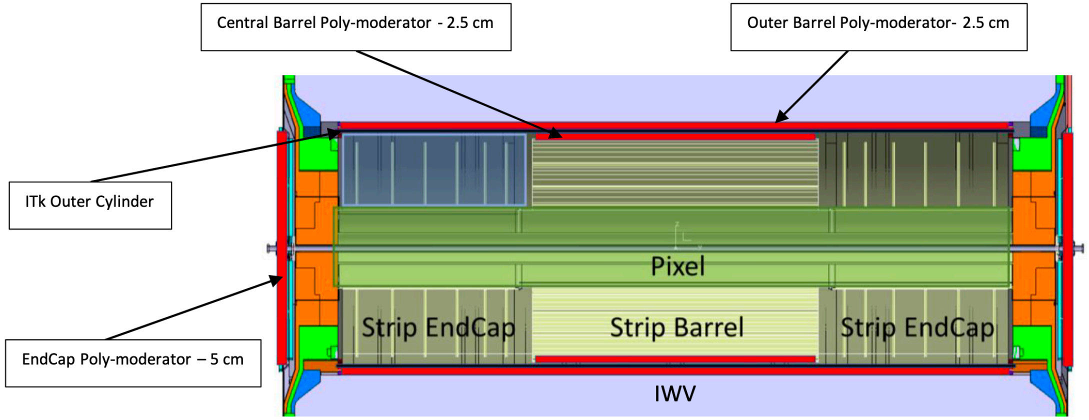
(http://www-library.desy.de/cgi-bin/showprep.pl?desy-thesis99-040)

Poly-moderator design to reduce damage fluence in the ITk.

1)

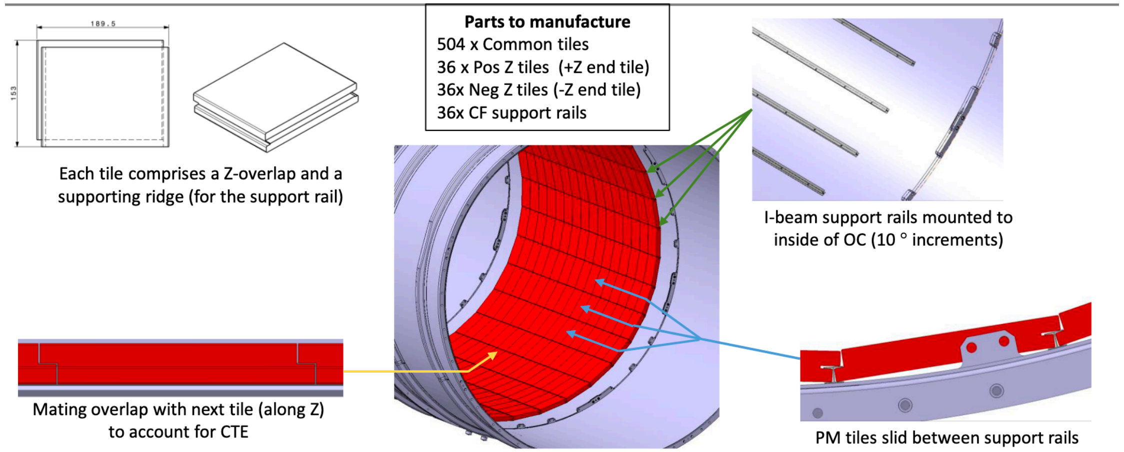


2)



Central Barrel Poly-moderator Design

3)



Each tile comprises a Z-overlap and a supporting ridge (for the support rail)

I-beam support rails mounted to inside of OC (10 ° increments)

Mating overlap with next tile (along Z) to account for CTE

Flat tiles arranged inside barrel region of OC to form a 2.5 cm thick layer of moderating material

PM tiles slid between support rails (Slide along Z)

4)

Testing for hole integrity


2832 bunches (1 bunch = 10^{11} proton)
Rotation frequency : 11 245 turns per second
1 collision per 25 nano-seconds
CMS
LHCb
ALICE
ATLAS