GEANT4 Study on Suitability of Diamond-Coated LPG Sensors

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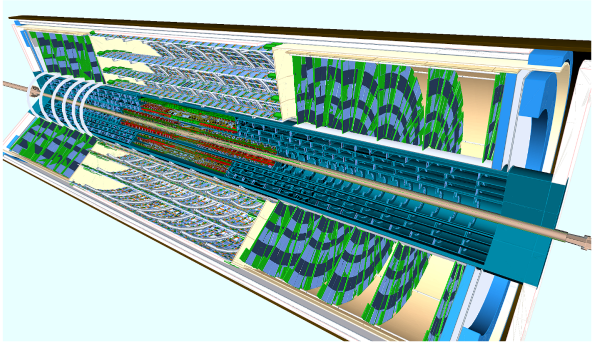
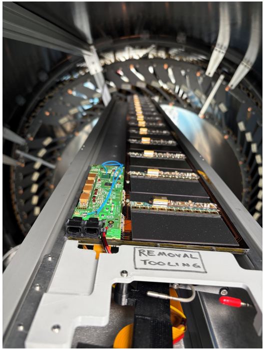
Humidity monitoring in HEP detectors

- ATLAS upgrade inner tracking detector $\rightarrow$ all silicon ITk
- Sensitive detector electronics cannot be exposed to moisture
- Need rad-hard moisture sensors to monitor enclosure environment
- Long Period Gratings have sensitivity to surface effects from coatings



(a) The ATLAS ITk design 3D model.



(b) A stave module being inserted into the barrel.

Current design and production

- Porous TiO_2 matrices are manufactured on bare LPGs with Sol-Gel process
- $\sim 100\,\mathrm{nm}$ layers build up to $\sim 1\,\mu\mathrm{m}$ with multiple dip-coatings
- Fibres currently used for this process are not Radiation-hard
- Damage mechanism seems to effect TiO_2 coating in addition to silica fibre
- Independent temperature and dose measurements must be made to remove these dependencies from the LPG responses and obtain the humidity-only signal

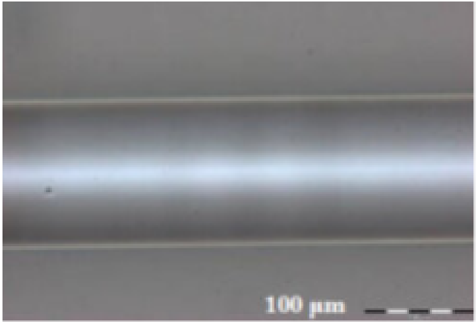


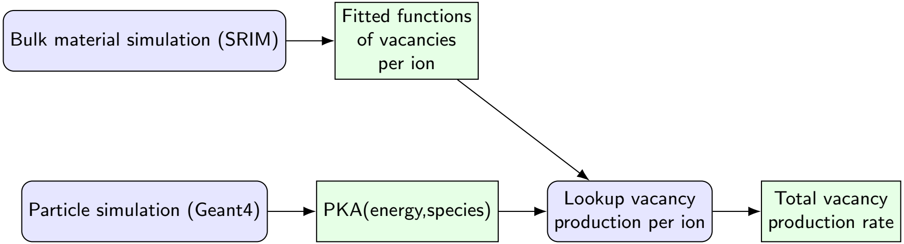
Figure: TiO_2 coating on an LPG

Diamond as a radiation hard alternative

- Aim to develop radiation-hard coating to apply to existing radiation-hard silica fibres
- Diamond is a radiation hard material with displacement energy; $E_d \simeq 40\,\text{eV}$ to $50\,\text{eV}$
- Silica $E_d \simeq 20\,\text{eV}$ to $25\,\text{eV}$ for Silicon nuclei and $E_d \simeq 15\,\text{eV}$ to $20\,\text{eV}$ for Oxygen nuclei
- Titania $E_d \simeq 25\,\text{eV}$ to $40\,\text{eV}$ for Titanium nuclei and $E_d \simeq 20\,\text{eV}$ to $30\,\text{eV}$ for Oxygen nuclei

Simulation workflow

- Simulate incoming particle flux with Geant4
- Extract Primary Knock-on Atoms with mass and energy
- Simulate PKA vacancy production with SRIM for each species and a range of energies
- Interpolate between energies with a fit function $V(E) = a + bE + cE^d$
- Sample fit functions for each PKA species and energy generated by Geant4 simulation to accumulate total vacancy production rate



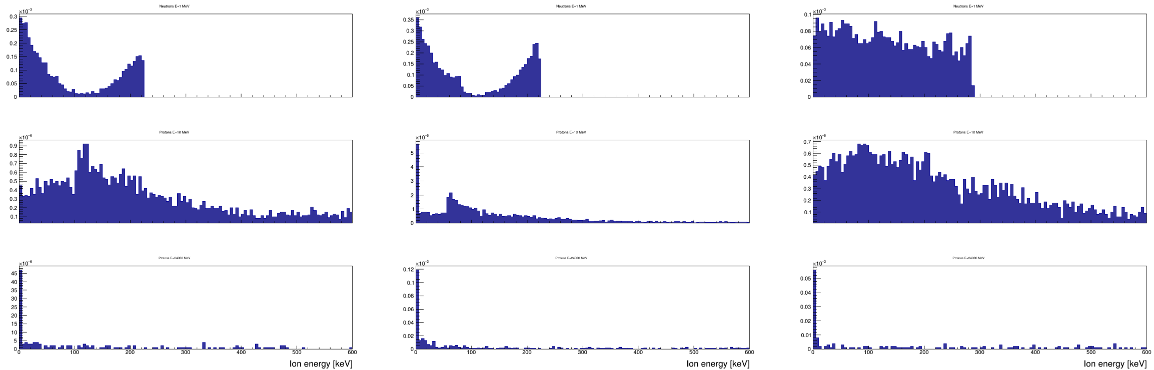
Absorbed dose

- The energy deposition in the simulated fibre is used to calculate absorbed dose per incident particle.
- For a given particle flux, this gives the dose rate.

Absorbed energy	Diamond	SiO_2	TiO_2
1 MeV neutrons	529.6 eV	364.9 eV	484.2 eV
10 MeV Protons	103.1 keV	92.38 keV	98.16 keV
24 GeV Protons	15.00 keV	10.42 keV	21.70 keV

Table: Energy deposition in fibre per incident particle

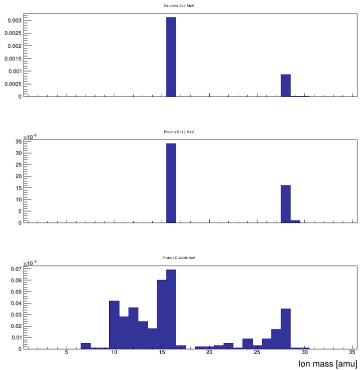
E.g. 1 MeV Neutrons give a dose of 2.17×10^{-10} Gy per neutron to silica.
With a flux of $3.64 \times 10^{14}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-1}$ (typical of reactor fast neutron flux) a dose rate of $618\,\mathrm{Gy\,s}^{-1}$ is realised.



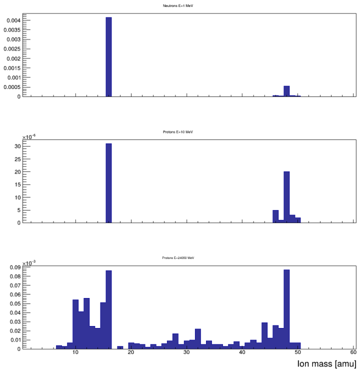
(a) Silica initial PKA energies (b) Titania (c) Diamond

For higher energy incident particles, a small elastic component gives low energy recoils while a long tail of high energy recoils is produced mostly from inelastic scattering.

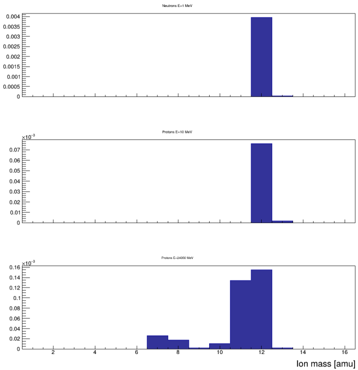
PKA masses



(a) Silica PKA masses



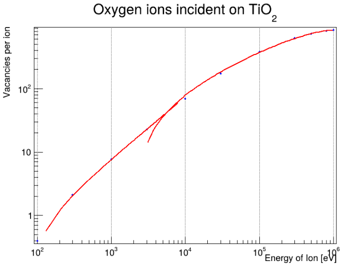
(b) Titania



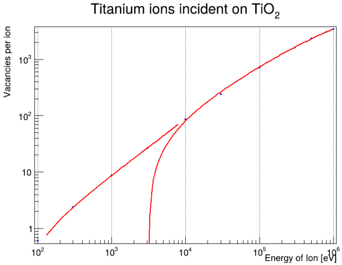
(c) Diamond

At the $24\,$GeV beam energy of the CERN IRRAD facility, nuclear reactions produce many recoil species.

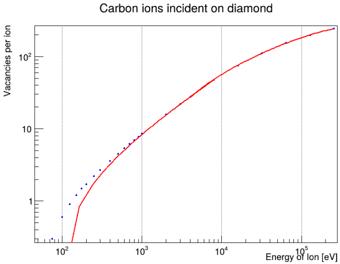
Vacancies per ion



(a) Oxygen PKA damage produced in titania.



(b) Titanium PKA damage produced in titania.



(c) Carbon PKA damage produced in diamond.

SRIM is used to simulate vacancies per ion with each species of PKA. This forms the dataset used to lookup the expected number of vacancies generated by a PKA in Geant4.

Total vacancy production

Folding the PKAs from Geant4 with the SRIM derived vacancy functions:

- TiO_2 suffers 1.462 vacancies per incident $1\,\mathrm{MeV}$ neutron
- TiO_2 suffers 0.0252 vacancies per incident $10\,\mathrm{MeV}$ proton
- Diamond suffers 0.730 vacancies per $1\,\mathrm{MeV}$ neutron
- Diamond suffers 0.0201 vacancies per $10\,\mathrm{MeV}$ proton

Work is ongoing to simulate mixed-radiation fluxes at higher energies to replicate conditions in HEP collider experiments.

Conclusions from the Geant4 Radiation Damage Study

- Geant4 simulations were used to investigate radiation-induced defect production in TiO_2 and diamond under high-energy particle irradiation.
- TiO_2 exhibited a significantly higher vacancy production rate, indicating greater susceptibility to radiation-induced lattice damage.
- Diamond produced substantially fewer vacancies under identical irradiation conditions, demonstrating superior radiation tolerance.
- The reduced defect generation in diamond suggests improved long-term structural and optical stability in harsh radiation environments.
- These results identify diamond as a promising candidate for next-generation radiation-hard optical sensing and environmental monitoring in high-radiation applications, such as the ATLAS ITk, nuclear facilities, and space systems.
- Future work: Develop the diamond-coated sensors and investigate the radiation damage to titanium-oxide experimentally.