Geant4-based simulations of microdosimetric data for high charge and energy particles

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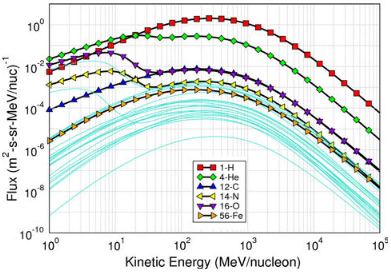
Space Radiation



Source: A. Keating *et al.*, 2012

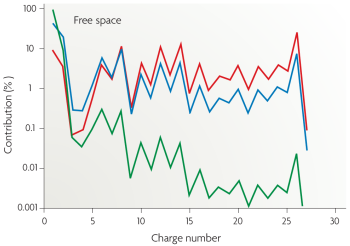


Figure 1 | **Space radiation environment and shielding.** The contribution in fluence (green), dose (blue), and dose equivalent (red) of different nuclei in galactic cosmic radiation.

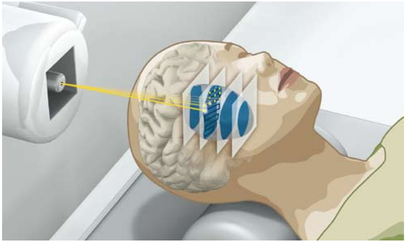
Source: M. Durante and F. Cucinotta, 2008

Detected particles from galactic cosmic rays (GCR) consist of 83% protons, 14% helium and 1% heavier nuclei. The maximum of the spectrum for specific nuclei is between 100-1000 MeV/u.

Several ions contribute differently to absorbed dose. Shielding is a problem due to high charge high energy (HZE) particles.

Radiation Effects by Ions (I)

Carbon ions of $\sim$300 MeV/u are successfully applied in cancer therapy.



Source: HIT

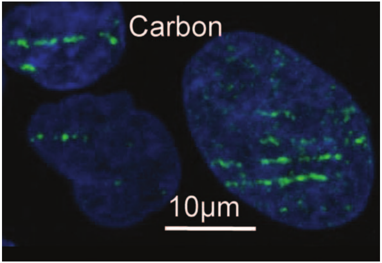
Source: NASA

Irradiation by ions from GCR is the major concern for human exploration at space.

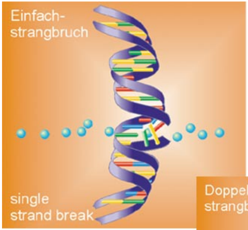
Better understanding of radiation effects due to ion tracks are required for ion beam cancer therapy and interplanetary human missions.

Radiation Effects by Ions (II)

9.5 MeV/u ^{12}C by in-beam microscopy.

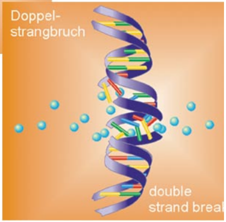


Source: B. Jakob *et al.*, 2009



Single strand breaks are usually repaired by the cell.

It is more difficult to repair double and multiple strand breaks.

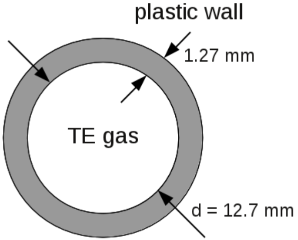


Energy imparted to tissue per unit of track length on scale of micrometres and nanometres matters to the biological action of radiation.

Microdosimetry Technique

Patterns of energy deposition on micrometer scale are measured by means of a Tissue-Equivalent Proportional Counter (TEPC).

Scheme of a typical walled TEPC



TEPC: a plastic sphere filled with low-pressure gas, equivalent to a few μm sphere of tissue, an object of a cell nucleus size.

Lineal energy: $y = \varepsilon/\bar{l}$
ε: energy deposited in the TEPC
$\bar{l} = \frac{2}{3}d$: mean chord length

TEPC is commonly flown on the ISS. TEPC is also applied for investigation of radiation effects at ground-based facilities.

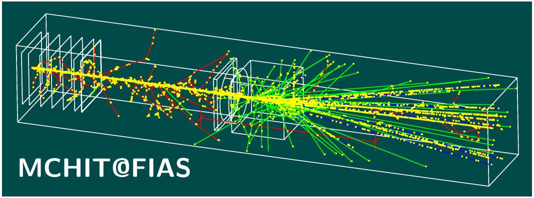
Monte Carlo simulations can be applied to investigate different scenarios of particle/energy/target in space.

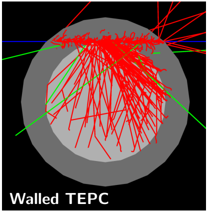
Monte Carlo Model for Investigation of Radiation Effects

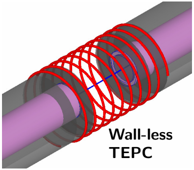
- The Monte Carlo model for Heavy-Ion Therapy (MCHIT) was developed at FIAS for benchmarking of Geant4 models to experimental data relevant to ion beam cancer therapy.

- MCHIT was extended for benchmarking of models to experimental data relevant to space research as well.

- Detailed implementation of TEPCs are applied for simulation of microdosimetric data for HZE particles.



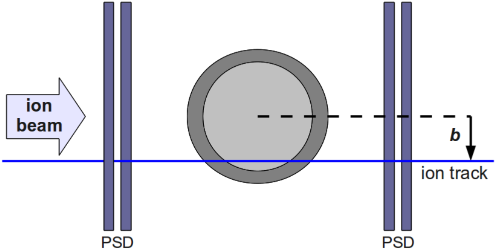




Characterization of TEPC at HIMAC and AGS

Experimental characterization of TEPC was performed at HIMAC and AGS with several ion beams in the energy range of 200-1000 MeV/u.

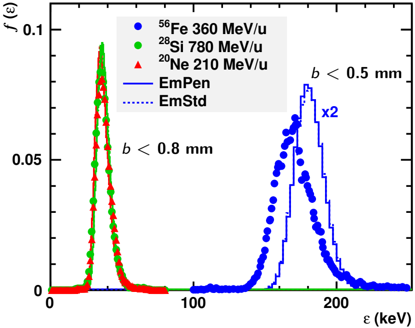
Experimental scheme



PSD detectors were used to evaluate impact parameter *b* and rule out events due to beam fragments.

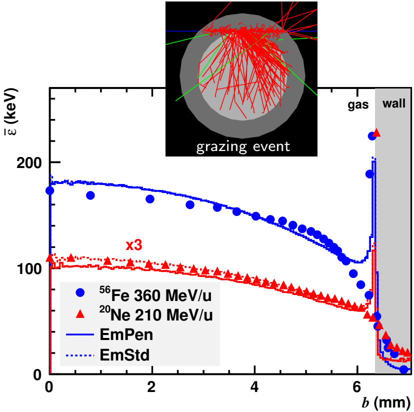
Experimental data can be used for benchmarking of electromagnetic models. G4EmStandard_opt3 (EmStd) and G4EmPenelope (EmPen) were used with threshold for production of δ-electrons set to 1 keV and 100 eV, respectively.

Response Function of TEPC



- The distribution of events for Ne and Si ions in central crossing of the detector are well reproduced. Energy deposition is overestimated for Fe ions.

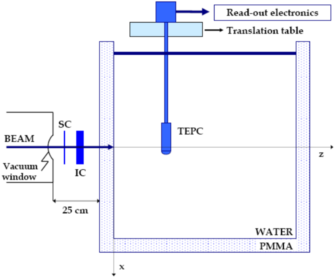
- The wall effect is reproduced by both set of electromagnetic models.



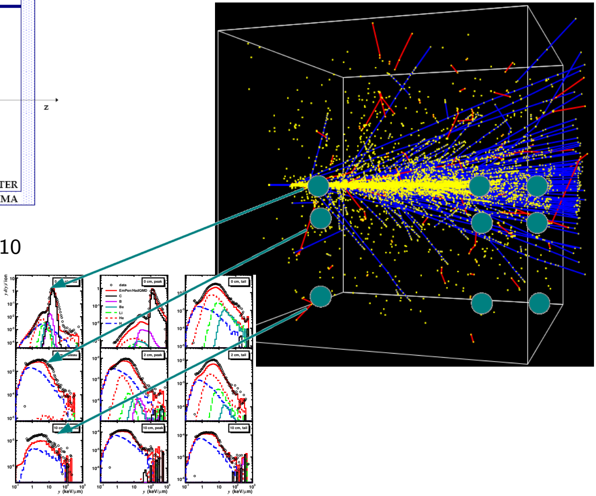
Source: L. Burigo *et al.*, 2013

TEPC Inside a Phantom at GSI

Irradiation by 185A MeV ^{7}Li and 300A MeV ^{12}C pencil-like beams.



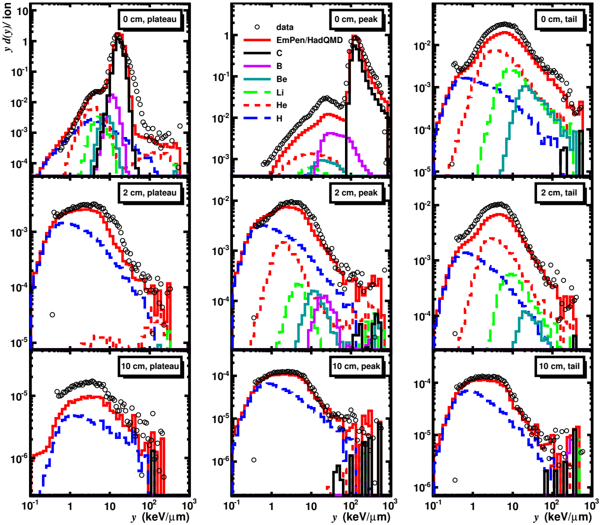
Source: G. Martino *et al.*, 2010



TEPC Measurements at Several Positions (I)

- Spectra on beam axis are mainly due to primary ion and heavy fragments.
- Only protons and neutrons contribute far from the beam axis.
- The contribution of secondary neutrons to the out-of-field dose from ^{12}C beams amounts to about 50% of the total far from the beam.

^{12}C 300 MeV/u

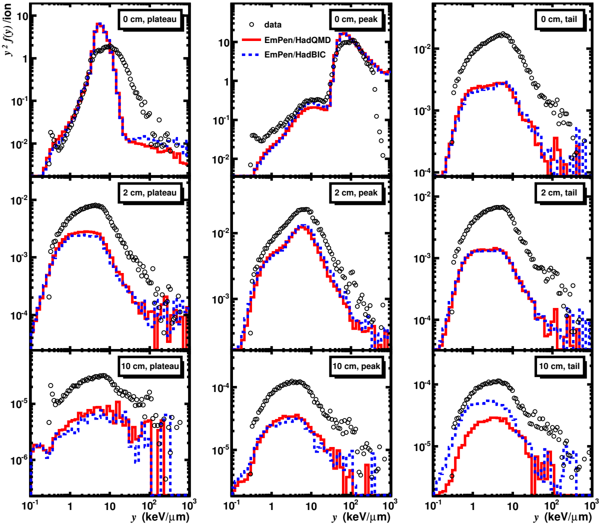


Source: L. Burigo *et al.*, 2013

TEPC Measurements at Several Positions (II)

- Hadronic models are not able to describe the measurements for ^{7}Li beam.
- There is still room for major improvements of Geant4 models describing propagation of ^{7}Li nuclei in water.

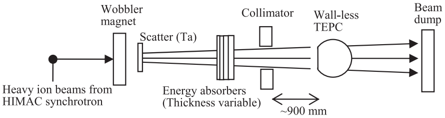
^{7}Li 185 MeV/u



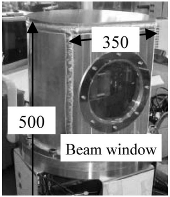
Source: L. Burigo *et al.*, 2013

Microdosimetry with Wall-Less TEPC at HIMAC (I)

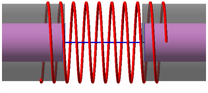
Wall-less TEPC behind a range shifter irradiated by H, He and Si ions.



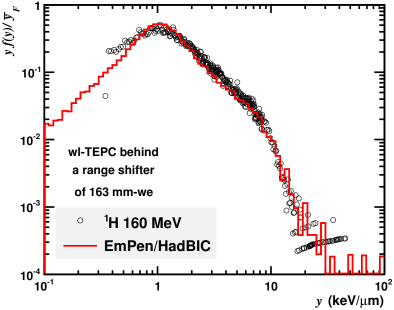
Wall-less TEPC behind a rage shifter. Measurements are sensitive to nuclear reactions.



Source: S. Tsuda *et al.*, 2012



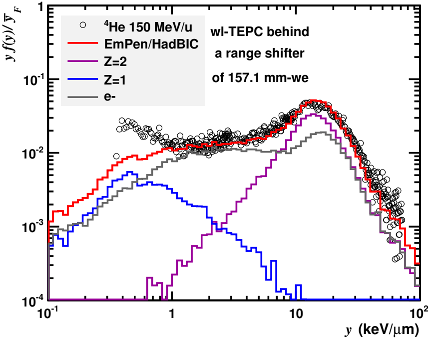
Internal geometry of wl-TEPC in MCHIT



- Calculated microdosimetric spectra for protons behind a range shifter with wall-less TEPC agree well with experimental data.

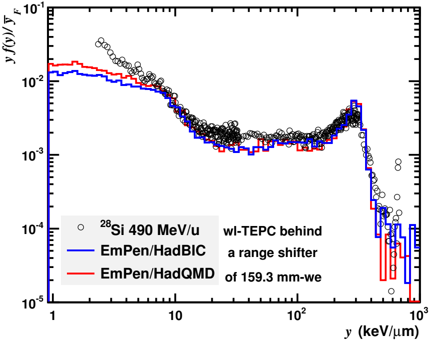
Source: L. Burigo *et al.*, 2013

Microdosimetry with Wall-Less TEPC at HIMAC (II)



- Disagreement at low y may be related to underestimation of yield of hydrogen-like fragments produced in nuclear reactions of helium ions.

- Simulations with hadronic models BIC and QMD present similar results.



Source: L. Burigo *et al.*, 2013

Conclusions

- Methods used to simulate detectors in nuclear and particle physics experiments are also successful for calculation of patterns of energy deposition on micrometre scale.
- With G4/MCHIT model one can calculate microdosimetric data for many ions and beam energies relevant for ion beam cancer therapy and space research.
- Microdosimetric spectra are equally well described by Geant4 electromagnetic models EmStandard_opt3 and EmPenelope.
- Measurements with TEPC inside or behind a phantom impose a challenge for hadronic models. Geant4 models are able to describe reasonably well microdosimetric spectra in the presence of nuclear fragmentation reactions.
- Further developments of nuclear fragmentation models for helium and lithium nuclei could improve the description of the microdosimetric data.

Thank you for your attention!

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Many thanks to
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Igor Pshenichnov
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