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Estimation of radiation damage to Wire Scanner carbon fiber on PS beam

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Summary

Carbon fibers which are used as fast moving targets in the beam wire scanners break after about 10^4 scans. The breakage mechanism is unclear as the estimated maximum temperature reached during scans is well below the range in which sublimation plays important role. Here a radiation damage has been considered. A special example of a carbon fiber passing a proton beam in PS at injection energy is investigated using SRIM code. The number of displacements per target atom is estimated. It is found to be small, therefore it is concluded that the radiation damage is not the mechanism leading to the wire breakage.

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1 Introduction

Various mechanisms might lead to carbon wire breakage in the particle beam. For very short and dense pulses of particles the mechanism might be the thermal shock as observed in Figure 4 of [1]. For less dense beams the wire material sublimates and a breakage might occur after a few scans. This type of the wire breakage mechanism has been investigated in [2] Finally wires break also, after thousands of scans, in the conditions which are far from the ones leading to strong sublimation. The mechanism of these breakage could be:

- slow sublimation, but this is in disagreement with simulations as well as observations [2, 3],
- thermal fatigue of the wire material,
- radiation damage.

In this report we estimate the radiation damage to the wire.

Stopping and Range of Ions in Matter (SRIM) [4] is a group of computer programs which calculate interaction of ions with matter. In this study version SRIM-2008.04 has been used.

A very simple target geometry has been introduced to SRIM: 28 micrometers of carbon target. In the SRIM library the carbon density is 2.253 g/cm^3, in comparison to $1.8 - 2.2$ g/cm^3 used in Geant4 and heat transfer simulations [3]. The other parameters, chosen automatically by SRIM as characteristic to carbon materials, are:

- lattice binding energy: 3 eV,
- surface binding energy: 7.41 eV,
- displacement energy: 28 eV.

The following reference beam parameters, corresponding to 25-ns LHC proton and ion beams [5], have been chosen:

- current: 72 bunches with $1.7 \cdot 10^{11}$ protons each
or: 2 bunches with $3 \cdot 10^8$ Pb^{54+} ions each,
- PS revolution time: 2.1 μs,
- beam width along the scan $\sigma_{\mathrm{x}} = 0.68$ mm,
- beam width along the fiber $\sigma_{\mathrm{y}} = 0.83$ mm,

The scan speed has been chosen to the present maximum achievable by the rotational wire scanners installed currently on the PS: 20 m/s.

The above parameters result in about $8.13 \cdot 10^{12}$ of the total amount of protons or $4 \cdot 10^8$ of the Pb^{54+} ions passing the wire during the scan.

2 Energy deposited in the fiber

The energy deposited in the fiber has been analysed in order to compare SRIM results with Geant4 simulations [3, 6]. The results of the SRIM simulation are shown on the left plot of Figure 1. The red area is a histogram, normalized to number of impacting protons, showing the energy loss expressed in electronvolt per angstrom of the target depth. The blue histogram, not visible here, shows energy lost to recoils. As it can be expected the electronic energy loss is the same along the whole depth of the thin target. The energy loss to recoils is much smaller than the electronic stopping.

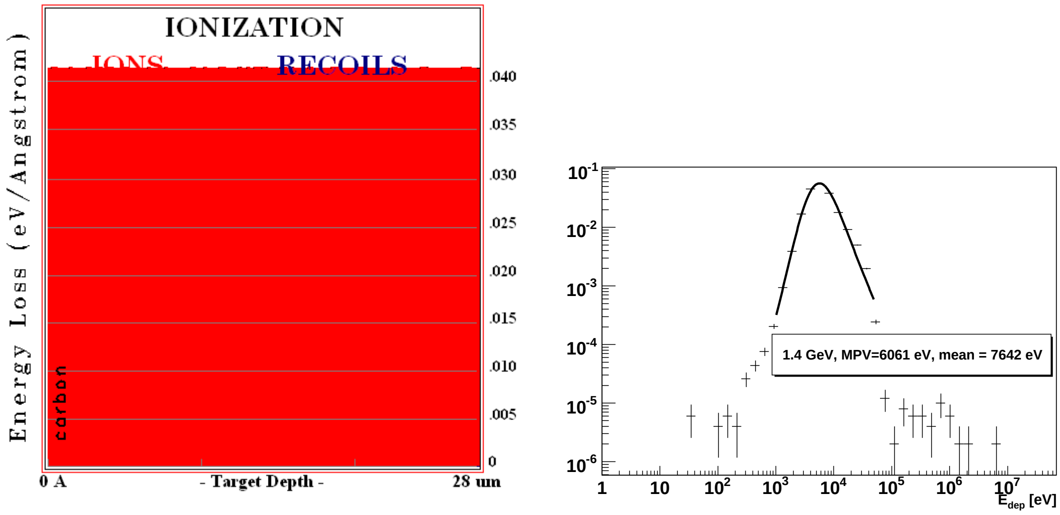

Figure 1: *The energy loss along the carbon wire as calculated by* SRIM *(left plot) and* Geant4 *(right plot).*

The total energy deposited in the carbon fiber by a single proton passing by the fiber center is about:

$$\mathrm{E_{dep}} = 0.041\,[\mathrm{eV/\AA}] \cdot\ 28 \cdot 10^4\,[\mathrm{\AA}] = 11.48\,[\mathrm{keV}] \tag{1}$$

In order to get average value of the energy deposition in the wire the correction on the cylindrical shape of the wire must be done. The correction factor is:

$$\mathrm{f_{cyll}} = \pi/4 \approx 0.785 \tag{2}$$

The value obtained from SRIM is about 20% higher than the mean value of energy deposition obtained with Geant4 simulations [6]. The reason for this difference is probably due to the fact that SRIM does not take into account the energy which is removed from the wire due to escaping electrons [7].

In case of Pb^{54+} ion beam the energy deposited has been calculated only by SRIM. It is shown in Figure 2. As in proton case the energy transfer to recoils is negligible with respect to the direct ionisation.

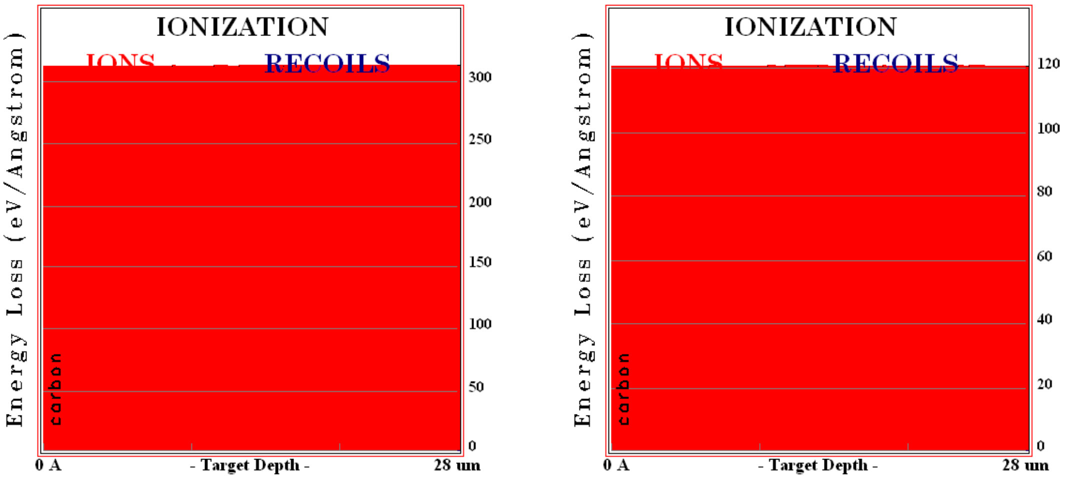

Figure 2: *The energy loss per Angstrom of the wire depth from* Pb^{54+} *along the carbon wire as calculated by* SRIM. *Left plot shows loss at injection energy (31 GeV) and the right plot at extraction energy (1227 GeV).*

A single Pb^{54+} with kinetic energy of 31 GeV deposits about 69 MeV of its initial energy in the wire. It is 7650 times more than a proton. In case of extraction energy the average energy loss is about 26.6 MeV. The effect of the knocked-off electrons is not estimated here. In the following we conservatively assume that in case of Pb^{54+} beam the electrons do not remove energy from the wire.

The maximum temperature evolution using the model [3] for proton and Pb^{54+} beams are shown in Figure 3. The ion beam is safer because of its smaller intensity.

3 Structural damage to material

The theory of radiation damage to the material (see for instance [8]) foresees that in case of energy transmission to an atom larger than so called displacement energy, the crystal structure of the material is permanently affected. The parameter which is used to describe the structural damage to the material is number of displacements per atom of the target (dpa).

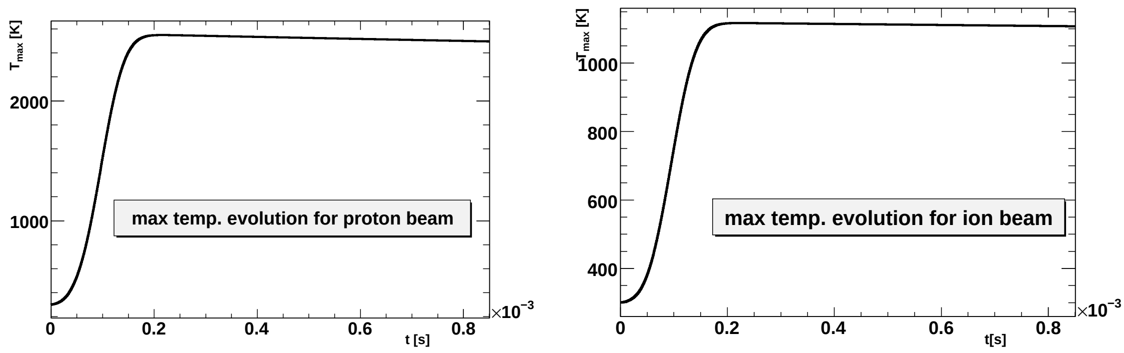

Figure 3: *The evolution of the maximum temperature of the wire during the scan of proton beam (left plot) and of lead ion beam at injection energy (right plot). The average energy deposited per proton/ion are taken from SRIM (no kick-out electron effect). The scan speed is 20 m/s.*

SRIM provides two options of calculation of the collision events, which lead to radiation damage of the material (eg. atom displacement). The fast option (called in SRIM menu: *Ion Distribution and Quick Calculation of Damage*) uses Kinchen-Pease model. In this model only the first generation of the recoiled atoms, ie. the ones produced directly by the incoming protons (or ions) is followed. In case of more precise calculations (called *Surface Sputtering / Monolayer Collision Steps*) every recoil atom is followed by the program. Unfortunately the Follow-Each-Recoil model demands a lot of processing power, therefore only a some of estimations has been confirmed with it.

The number of point defects generated by the impacting ion is derived analytically from the energy that is transferred from an ion to an atom of the target material. It is assumed that the number of point defects generated by a primary recoil is proportional to the energy transferred from the ion to the primary recoil. A primary recoil is a recoil generated by the collision of the impacting proton with a target atom, while secondary recoils are generated by recoils.

3.1 Proton beam

The total amount of vacancies created by primary ions and the first recoils is about $8.87 \cdot 10^{-7}$ per Angstrom and per proton. This gives about $2.48 \cdot 10^{-3}$ displacements per proton passing the wire center or $1.95 \cdot 10^{-3}$ if one takes into account cylindrical shape of the wire (Equation 2). The distribution of the displacements along the wire diameter is shown in on left plot of Figure 4 for fast calculation (with about $3.8 \cdot 10^7$ protons) and on the right plot for full calculation (about $1.3 \cdot 10^5$ protons).

The fast calculation features a rise of the damage level with the target depth. This effect is not expected for a thin target like the carbon fiber. The full calculation, despite of relatively small statistical error, suffers from small available statistics.

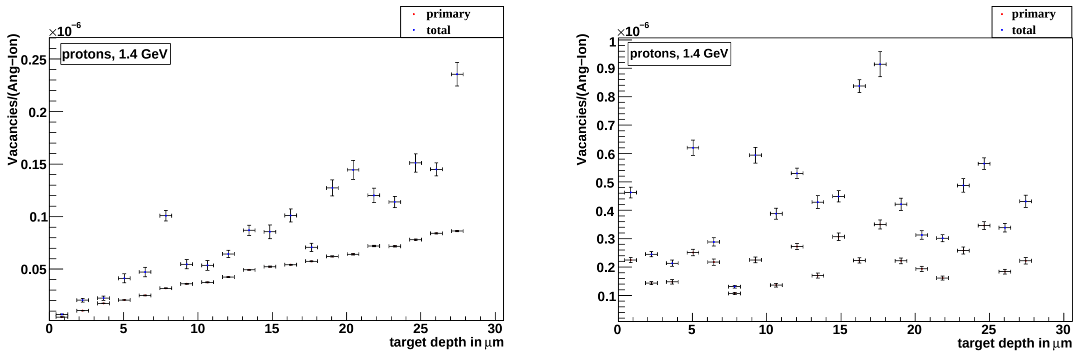

Figure 4: *The amount of collision events along the wire calculated using fast Kinchen-Pease model (left plot) and the full simulation (right plot). The blue points show total damage and the red ones show damage provoked by the direct proton interaction.*

The amount of atoms in the wire section with height equal to beam width σ_y is:

$$N_{atom} = 0.18 \text{ mole/cm}^3 * N_{avog} * \pi * d^2/4 * \sigma_y = 5.54 \cdot 10^{16} \quad (3)$$

Therefore a single scan provokes $3.51 \cdot 10^{-7}$ displacements per atom (dpa). Ten thousand scans give $3.51 \cdot 10^{-3}$ dpa. This is well below the visible radiation level damage.

The full simulation gives results a factor 20 worse: after 10^4 scans the damage to the material is expected to be around $3 \cdot 10^{-2}$ dpa. This shows the importance of the damage due to the recoils which are produced already by previous recoils. Nevertheless the obtained values of the structural damage are still very small.

3.2 Pb^{54+} ion beam

The Pb^{54+} ion has the same width as the proton beam, but its intensity is smaller. Here the injection (31.2 GeV) and extraction (1227.2 GeV) lead ion energies were considered. The simulation has been carried out with $2.5 \cdot 10^6$ (injection) and $4.7 \cdot 10^6$ (extraction) ions. The number of collision events for is shown in Figure 5 for injection (left plot) and extraction (right plot) energies.

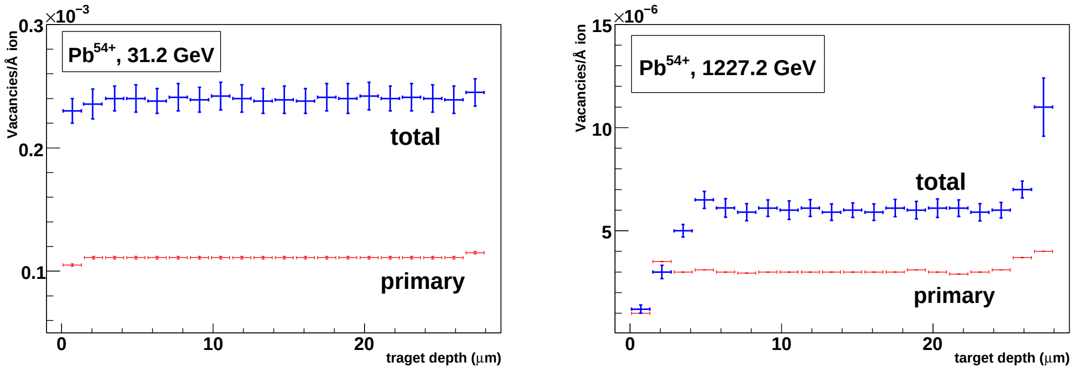

Figure 5: *The amount of collision events along the wire hit by Pb^{54+} ion calculated using fast Kinchen-Pease model. The more-energetic beam cause about 40 times less damage.*

At injection energy a single ion passing the wire center produces $2.35{\cdot}10^{-2}$vacancies per Angstrom. The collision events is mainly due to recoils, and not primary ions. The 10^4 scans provoke radiation damage of $3.58 \cdot 10^{-3}$ dpa.

At extraction energy the average number of vacancies per ion and Angstrom is even smaller: $6.11{\cdot}10^{-3}$. Therefore, total damage to the wire material is $0.93 \cdot 10^{-4}$ dpa.

4 Conclusions

It can be concluded that in case of wire breakage after about ten thousand scans the radiation damage is small and cannot cause the breakage.

In addition it has been observed that SRIM code gives systematically higher values of energy deposition in thin target than Geant4 code. The reason is probably missing treatment of kick-off electrons.

Finally, based on proton example it might be concluded that the recoils of the second generation and later produce significantly more damage than primary events and first generation of recoils. This conclusion is based on comparison of the results from approximate Kinchen-Paese model and from the exact model (full simulation). But even in case of the exact calculation the radiation damage remains about 2 orders of magnitude below the level when the measurable changes to carbon properties occur.

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