Simulating radiation damage effects in LHC collimators (code development status)

R. Assmann, H.-H Braun, A. Ferrari, S. Gilardoni, J.M. Jowett, G.I. Smirnov and V. Vlachoudis

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1. Introduction

Radiation damage in graphite :

1. **Dimensional** changes
    - a. length
    - b. diameter
    - c. volume
2. **Property** changes
    - a. thermal conductivity (reduction)
    - b. electrical resistivity (increase)
3. **Structure** changes
    - a. Hydrogen (and helium) retention
    - b. Surface sublimation

LHC collimator jaws ➡

AC150K Tatsuno, Jpn.

2D C/C (CFC) composite

2. Role of theoretical and model uncertainties

- Monte Carlo models for secondary and recoil particles (recoil spectra, damage energy)

  p* + C → *p* + *X at 7 TeV

  X : 12C, 11C, …, 4He, 3He, t, D, ***p*, *n***, pions, ...

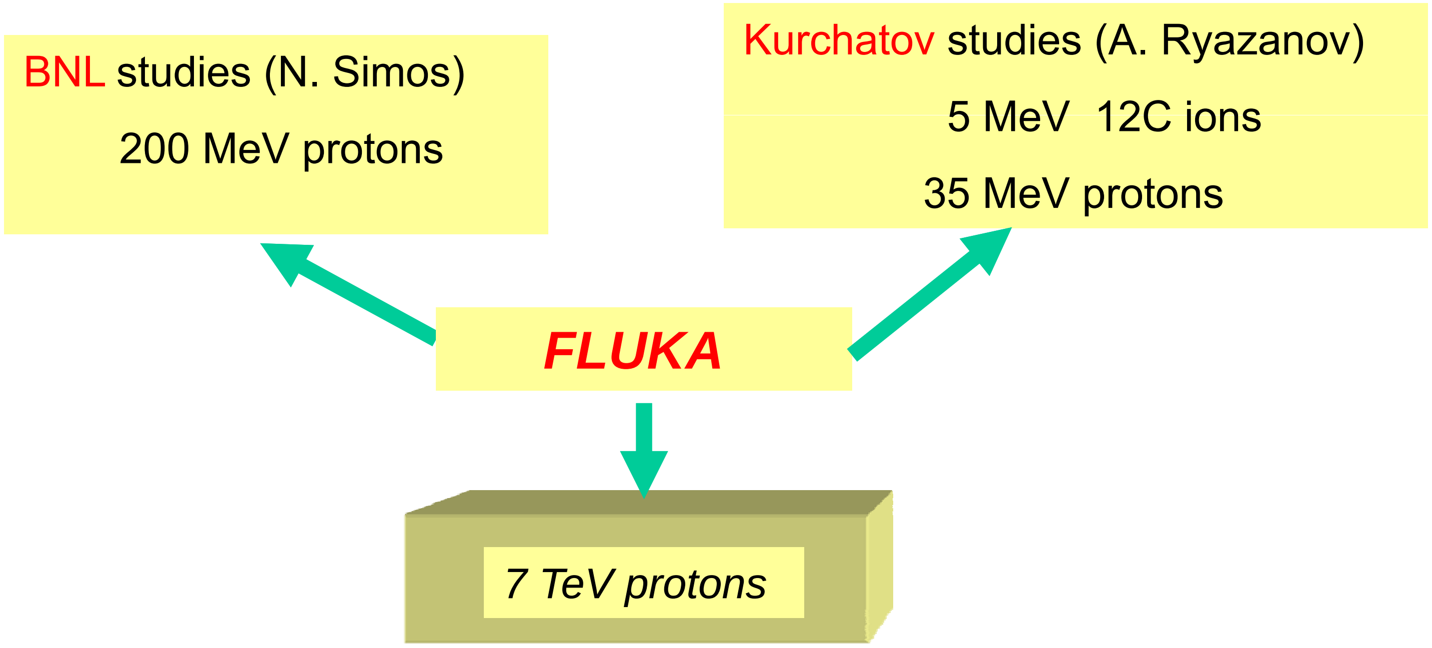
- **Dpa** damage functions can be different if calculated in the USA or Europe —

  different models are used for :

  1. Evaluation of the partitioning of damage energy between **ionisation** and **displacements**
  2. Treatment of the displaced atoms **motion** and **recombination**:
     a) Binary collision approximation (BCA)
     b) Molecular dynamics (MD) approach

- **Major uncertainty** is anticipated in establishing relation between **dpa** and macroscopic damage effect

- Results of experimental tests of CFC (various beams, different energies) must be analyzed together with the Monte Carlo simulation results.



BNL studies (N. Simos)

200 MeV protons

Kurchatov studies (A. Ryazanov)

5 MeV 12C ions

35 MeV protons

FLUKA

7 TeV protons

3. Algorithms for dpa calculation

Number of defects in the modified Kinchin-Pease model:

Norgert-Robinson-Torrens (**NRT**)*

$$N_D = 0.8\ \mathrm{NIEL} / 2E_{th}$$

Total number of defects for one kind (***i***) of particles (fragments) initiating cascades:

$$N_D^{\mathrm{tot}(i)} = \int (dN_D^{(i)}/dE)\, dE$$

Total damage in terms of displacements per atom:

$$\mathrm{dpa} = 1/\,(N_A\ \rho/A)\ \Sigma N_D^{\mathrm{tot}(i)}$$

*

- Also used in NJOY
- CFC — displacement threshold energy E_{th} = 35 eV

Energy transfer to the lattice atom
« *partition function* »

Theories : 1) Lindhard (Lindhard, Nielsen and Scharf)
2) Firsov

Partition of the primary recoil energy $\boldsymbol{E}$:

$$E = E_1 + E_2$$

Where E_1 is nonionising energy loss (NIEL)
E_2 is ionisation loss

Three region in the Lindhard theory:

1) Nuclear stopping is dominating
2) Nuclear stopping starts decreasing
3) Ionisation loss dominates

Results from Lindhard and Firsov theories conviniently represented by T. Robinson as:

NIEL = 0 if $E < E_{th}$ (threshold energy)

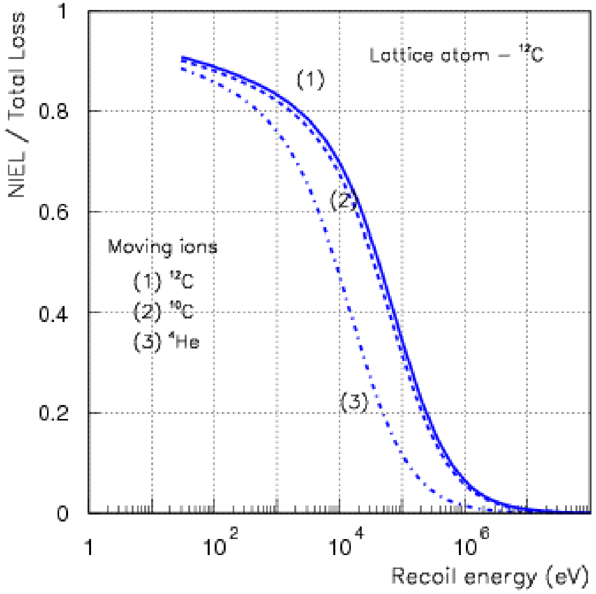
$$f_{\mathrm{NIEL}} \equiv \frac{\mathrm{NIEL}}{E} \,,$$

$$f_{\mathrm{NIEL}}(E) = \frac{1}{1 + F_L(3.4008\epsilon^{1/6} + 0.40244\epsilon^{3/4} + \epsilon)} \,,$$

where E is the recoil energy, $\epsilon(E) = E/E_L$,

$$E_L = 30.724 \cdot Z_1 \cdot Z_2 \cdot \left(Z_1^{2/3} + Z_2^{2/3}\right)^{1/2} \frac{A_1 + A_2}{A_2} \,,$$

$$F_L = 0.0793 \frac{Z_1^{2/3} \cdot Z_2^{1/2}}{\left(Z_1^{2/3} + Z_2^{2/3}\right)^{3/4}} \frac{(A_1 + A_2)^{3/2}}{A_1^{3/2} A_2^{1/2}}$$

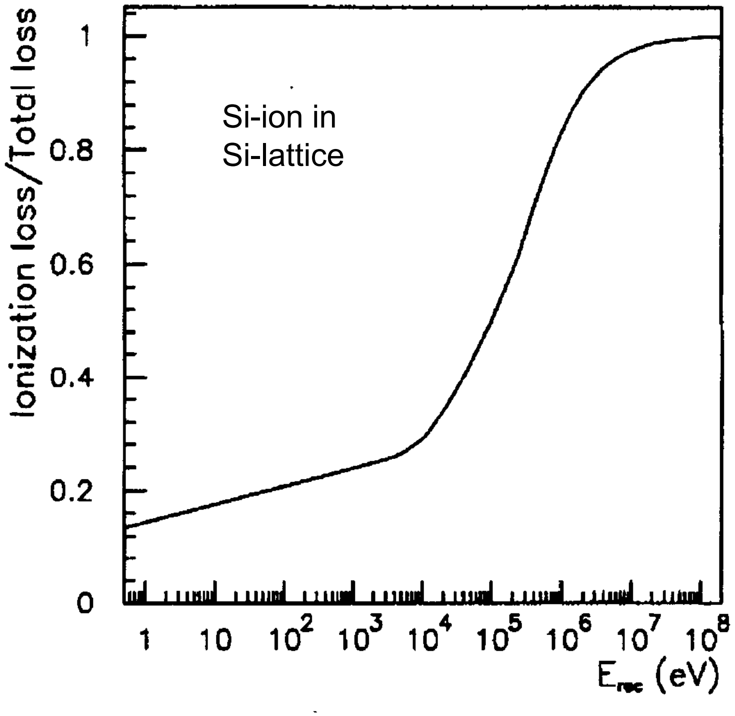


Non ionizing energy loss — **NIEL** in Carbon lattice for 4He, 10C and 12C

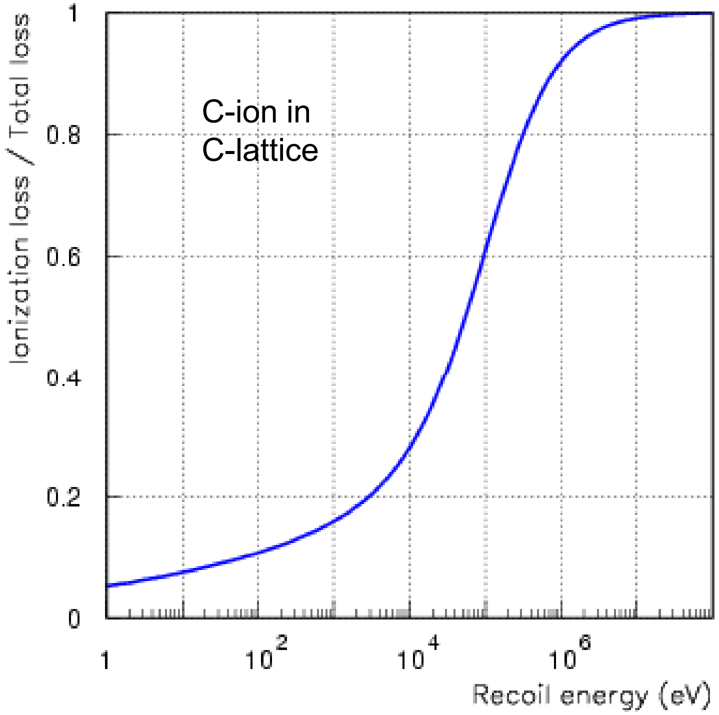
« Partition function »

Portion of recoil energy going into ionization

Lindhard theory



Robinson



Average threshold energy *

Element	Energy (eV)
Carbon	31
C in SiC	20
Graphite	30, 35
Al	27
Si	25
Mn	40
Fe	40

Element	Energy (eV)
Co	40
Ni	40
Cu	40
Nb	40
Mo	60
W	90
Pb	25

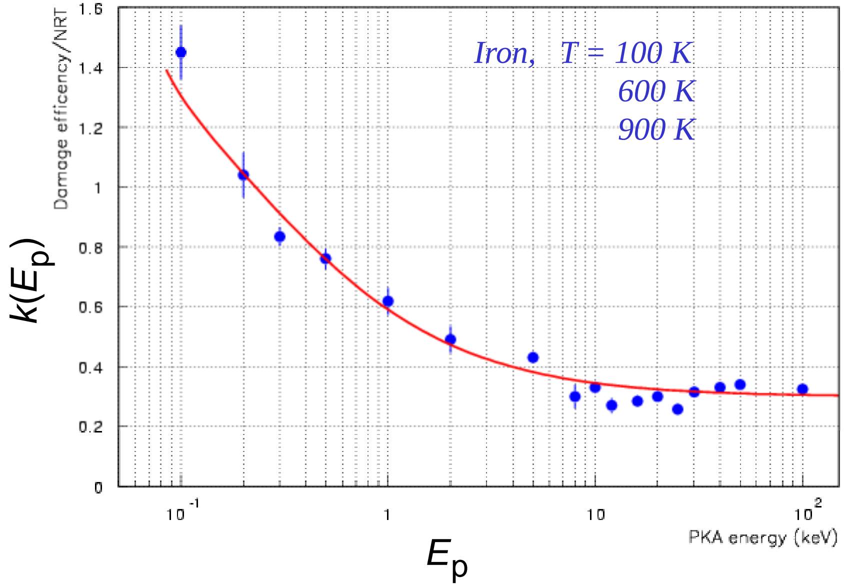
* Some typical values used in the NJOY99 code system

Cascade damage formation

Lifetime of defects — *10 ps*

Molecular dynamics for cascade evolution: R. E. Stoller, *J. Nucl. Mat.*, 276 (2000) 22

- weak dependence on the material
- virtually independent on temperature
- larger damage for near surface cascades



Number of defects :

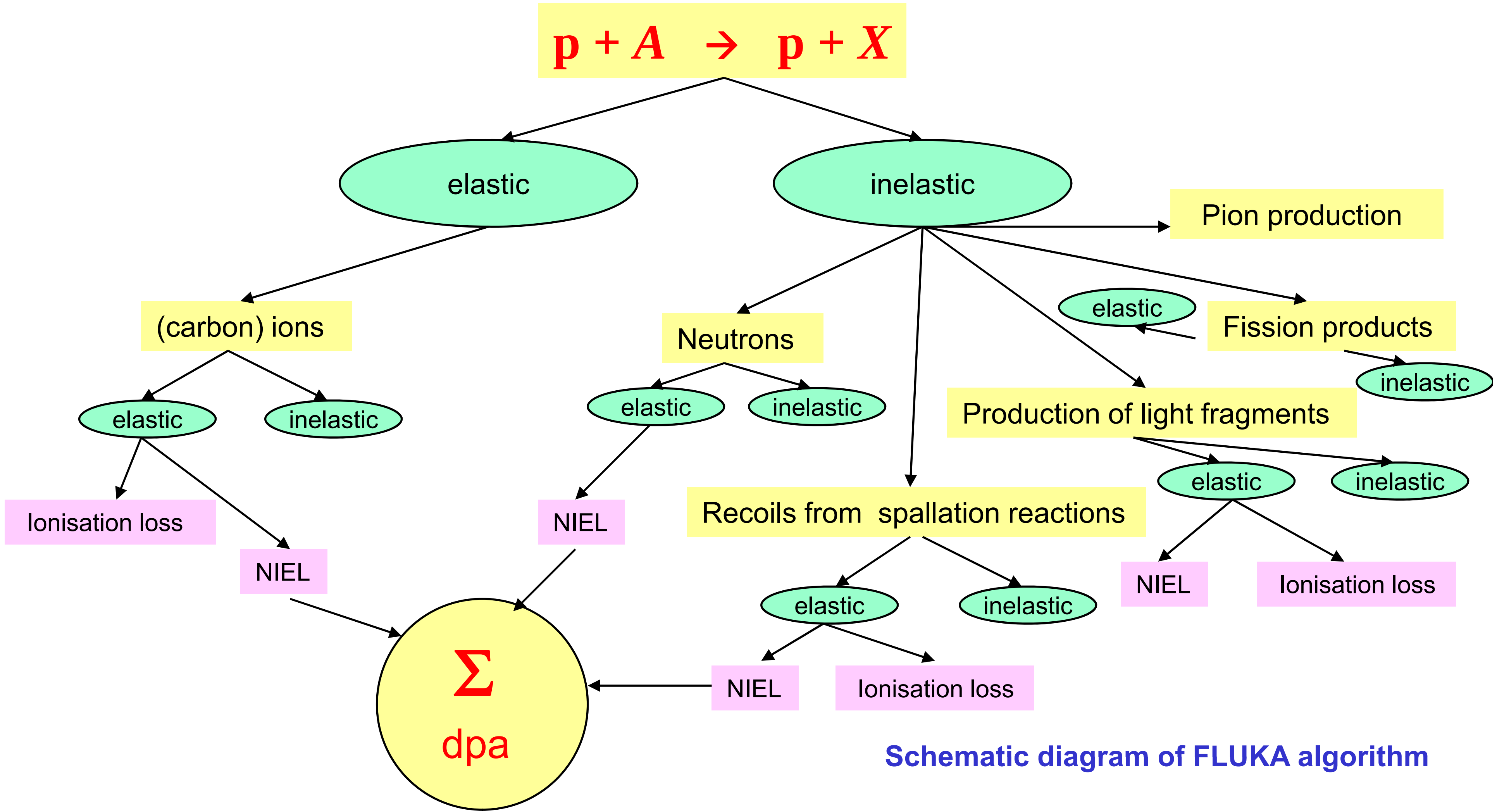
$N_D = k$ NIEL / $2E_{th}$

Solid line — *our approximation :*

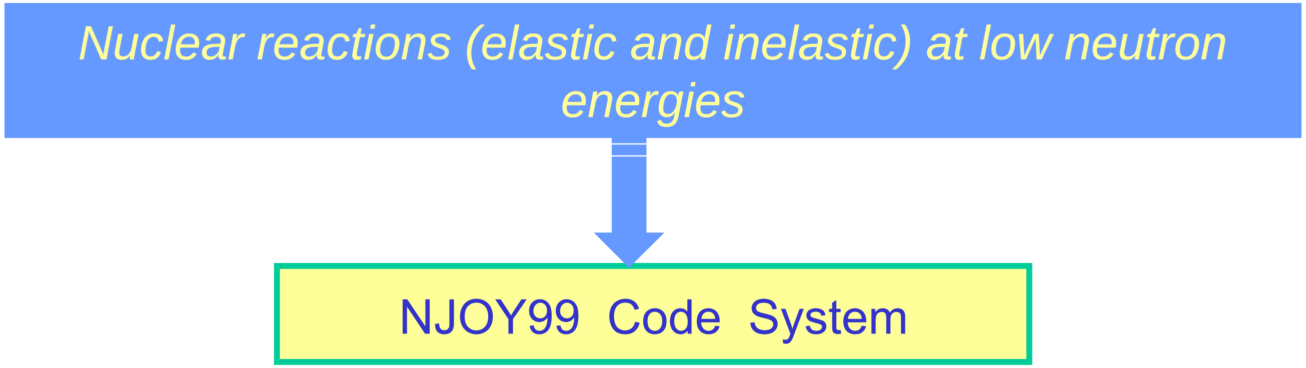
$$\kappa(E_p) = 0.3 - 1.3\left(\frac{A}{X} + \frac{B}{X^{4/3}} + \frac{C}{X^{5/3}}\right) ,$$

where parameters A, B and C are -9.57, 17.1 and -8.81, respectively, and $X \equiv 20E_p$.

4. FLUKA upgrade



Schematic diagram of FLUKA algorithm



Nuclear reactions (elastic and inelastic) at low neutron energies

NJOY99 Code System

Modular computer code used for converting evaluated nuclear data files (ENDF) into libraries useful for applications calculations.

NJOY99 (latest release of the NJOY system) handles a wide variety of nuclear effects in the energy range from thermal neutrons up to 150 MeV.

5. Summary

Damage effects in LHC collimator jaws evaluation:

- FLUKA Monte Carlo code
- Binary collision model (primary cascades)
- Results from Molecular Dynamics simulation (recombination of defects)
- Results from NJOY (nuclear effects in ***nA*** reactions below 150 MeV)
- Cross checks by employing results of CFC irradiation at low energies

Only protons, neutrons and pions are expected to be important for the radiation effects in CFC material at LHC energies