Energy Losses of Magnetic Monopoles

Z. Sahnoun for the Bologna Group

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Monopole Energy Loss

- *Fast Monopoles* ($\beta > 10^{-1}$)
  Bethe-Bloch; equivalent electric charge $(ze)_{eq} = g_D\beta$

- *Slow Monopoles* ($10^{-4} < \beta < 10^{-2}$)
  Ionization or excitation of atoms and molecules of the medium

- *Monopoles at very low velocities* ($\beta < 10^{-5}$)
  Monopoles interact with the magnetic moment of atoms, elastic collisions.

Energy Loss of fast Monopoles $(\beta > 10^{-1})$

Bethe-Bloch formula adapted to magnetic charges

S.P. Ahlen, Phys. Rev. D 17 (1978) 229.

$$-\frac{dE}{dx} = C\,\frac{Z}{A}\,g^2\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \frac{1}{2} + \frac{k}{2} - \frac{\delta}{2} - B_m\right] \quad \mathrm{MeV g^{-1} cm^2}$$

with $C = \frac{e^4}{m_u\, 4\pi\epsilon_0^2 m_e c^2} = 0.307\ \mathrm{MeV g^{-1} cm^2}$ and $g = n g_D = n \cdot 68.5$

δ the density effect

k, Bm The QED and Bloch corrections

Material	ρ (g/cm^3)	N_e (cm^{-3})	I(eV)
Al	2.699	7.83×10^{23}	$166\exp(-0.056/2)$
Fe	7.874	2.2×10^{24}	$285\exp(-0.14/2)$
Cu	8.96	2.46×10^{24}	$322\exp(-0.13/2)$

Energy loss of slow monopoles ($10^{-3} < \beta < 10^{-2}$)

Medium approximated as a degenerate electron gas.

S.P. Ahlen and K. Kinoshita, Phys. Rev. D 26 (1982) 2347.

$$-\frac{dE}{dx} = C\,\frac{Z}{A}\,\frac{c}{2v_F}\,g^2\,\beta\left[\ln\frac{2m_e v_F \Lambda}{\hbar} - 0.5\right] \quad \mathrm{MeV g^{-1} cm^2}$$

$v_F = (\hbar/m_e)(3\pi^2 N_e)^{1/3}$ is the Fermi velocity

For conductors: there are two terms

$$-\frac{dE}{dx} = \left(-\frac{dE}{dx}\right)_{bulk} + \left(-\frac{dE}{dx}\right)_{conduction}$$

N_e Bulk and Λ Bohr

N_e Cond and $\Lambda = \frac{50\,a\,T_m}{T}$

Material	N_{eCond} (cm^{-3})	N_{eBulk} (cm^{-3})	v_{FCond} (cm/s)	v_{FBulk} (cm/s)	T_m (K)
Al	18.2×10^{22}	6.011×10^{23}	2.03×10^{8}	3.024×10^{8}	933.52
Fe	17×10^{22}	2.03×10^{24}	1.98×10^{8}	4.54×10^{8}	1811
Cu	8.47×10^{22}	2.38×10^{24}	1.57×10^{8}	4.78×10^{8}	1358

For **Aluminun**

$$-\frac{dE}{dx}(Al) = (13.7 + 80) \times n^2\beta \quad (\mathrm{GeVg^{-1}cm^2})$$

Consistent with results from G.Giacomelli, Rivista Nuovo Cim. Vol.7 n.12 (1984) 1.

For **Iron**

$$-\frac{dE}{dx}(Fe) = (18.9 + 28.4) \times n^2\beta \quad (\mathrm{GeVg^{-1}cm^2})$$

Consistent with results from J. Derkaoui et al. , Astrop. Phys. 9 (1998) 173; for same values of density and temperature.

For **Copper**

$$-\frac{dE}{dx}(Cu) = (19.45 + 14.54) \times n^2\beta \quad (\mathrm{GeVg^{-1}cm^2})$$

Energy loss at low velocities ($\beta < 5.10^{-4}$)

The main contribution is due to elastic collisions of monopoles with atoms and nuclei.

-> magnetic field of the monopole with the magnetic moment of a structureless atom

For Silicon:

$$\frac{dE}{dx}(Si) = \left(0.79\frac{\text{MeV}}{\text{g/cm}^2}\right)\left(\frac{g}{137e}\right)^2 \times \left[13.12 + \ln\beta - \ln\left(\frac{g}{137e}\right)\right]$$

S. P. Ahlen and K. Kinoshita Phys. Rev. D 26 (1982) 2347

More accurate computations to be done as in J. Derkaoui et al. Astropart. Phys. 9 (1998) 173.

-> Potential between a MM and atoms of the form:

$$V(R) = \begin{cases} V_0\, e^{-aR} & \text{for } R < 0.3, \\ \dfrac{0.097 Z n^2}{R^4} & \text{for } R > 0.3, \end{cases}$$

with $V_0 = \dfrac{13.6 Z^2 n}{n+1}$ eV   excitation of the level 1s, m_j=-1

-> From the trajectories: relationship between the impact parameter *b* and the scattering angle θ.

ㅍ $\sigma(\theta) = -\dfrac{db}{d\theta}\dfrac{b}{\sin\theta}$.   ㅍ $-\dfrac{dE}{dx} = N \int \sigma(K)\, dK$

K : the kinetic energy transfer

Energy loss at very low velocities ($\beta < 10^{-5}$)

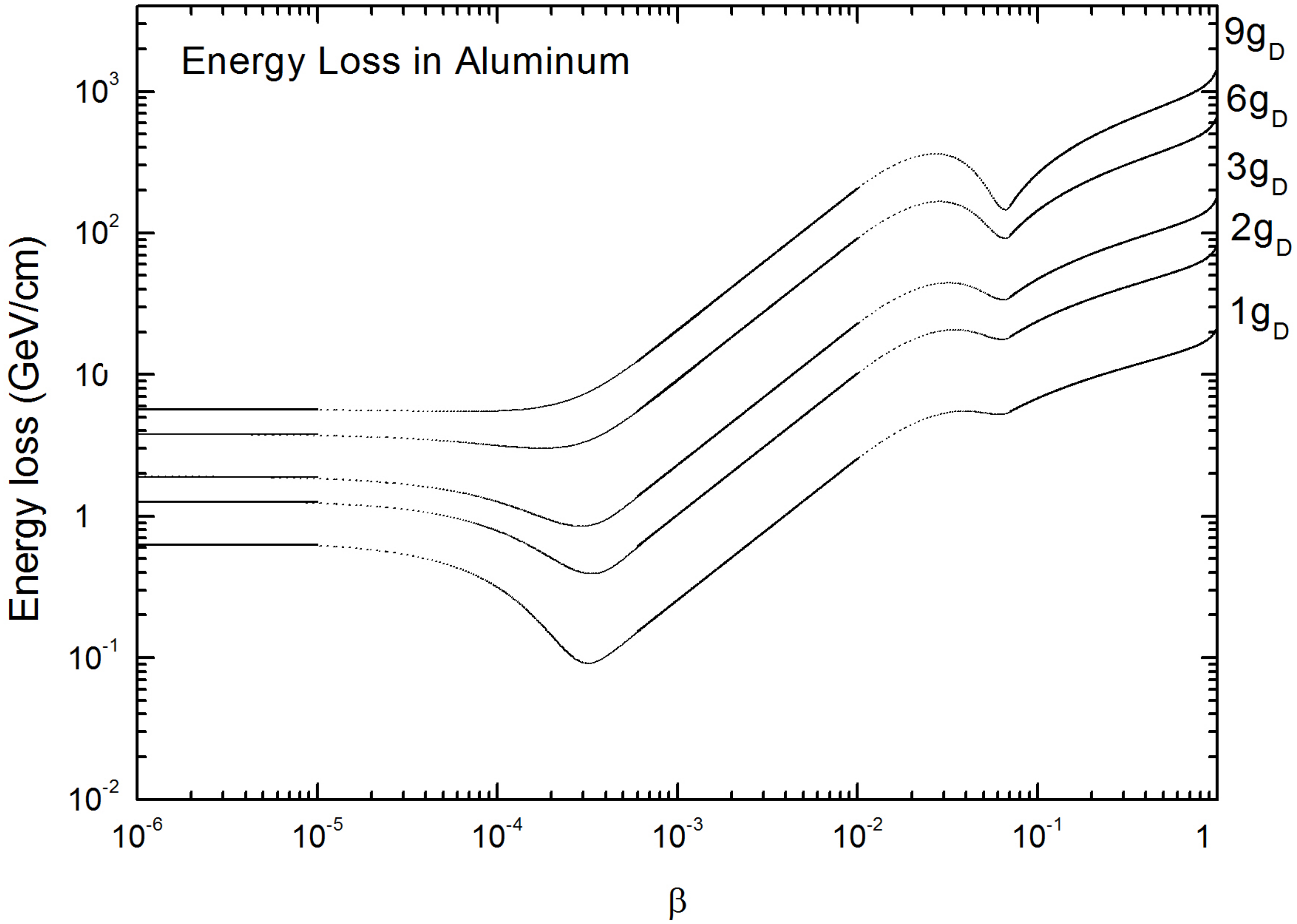
Paramagnetic materials: Monopoles interact with the atom magnetic moment.

L. Bracci, G. Fiorentini, R. Tripiccione, Nucl. Phys. B 238 (1984) 167.

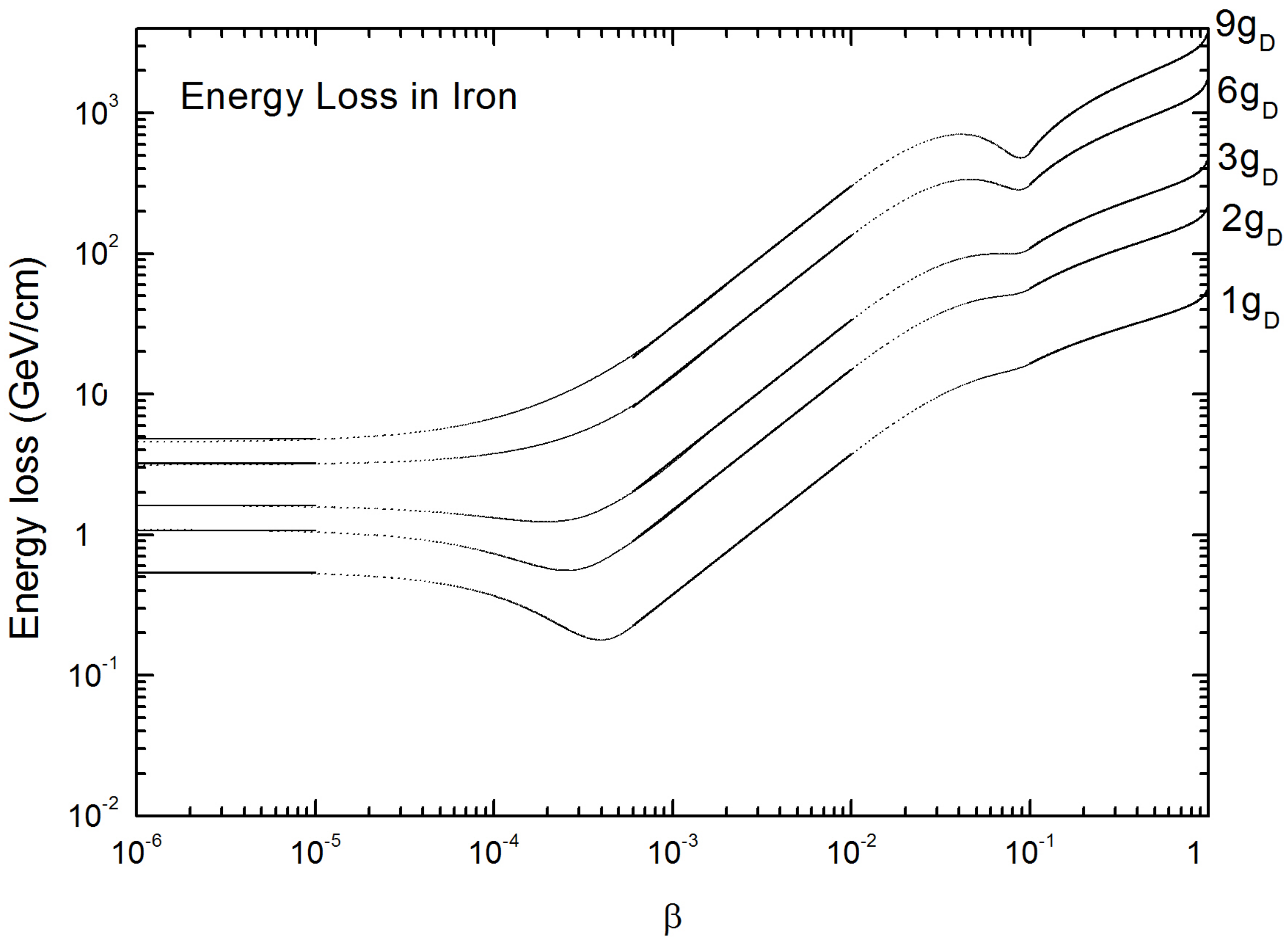
$$-\frac{dE}{dx} = \mu \times \frac{4\pi\hbar\, g\, e\, N}{c\, m_e} \times 0.6$$

For Aluminum, μ = 3.64; (in Bohr magneton)
for Iron, μ = 2.20;
for Copper, μ = 2.22.

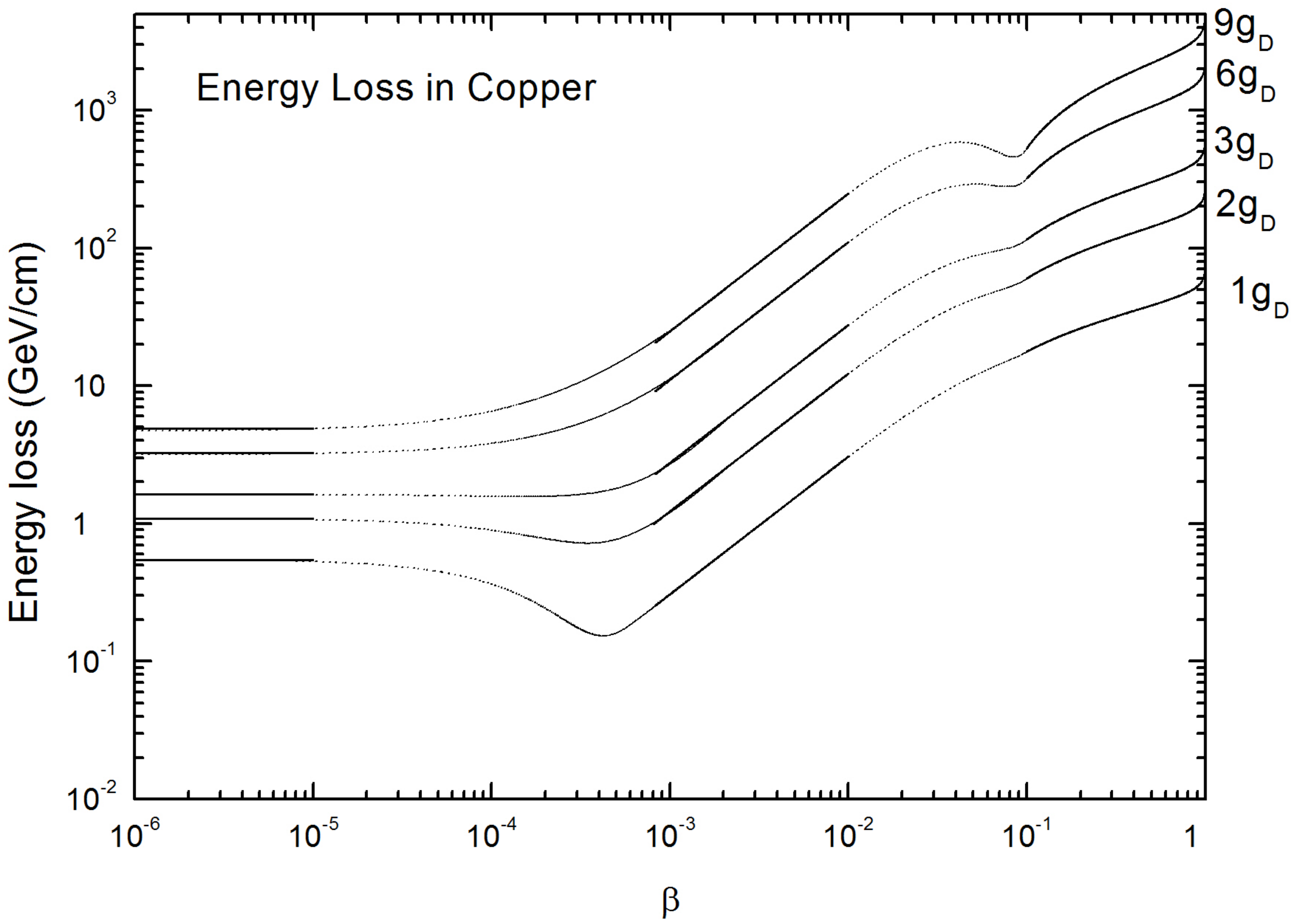
Energy loss in Aluminium



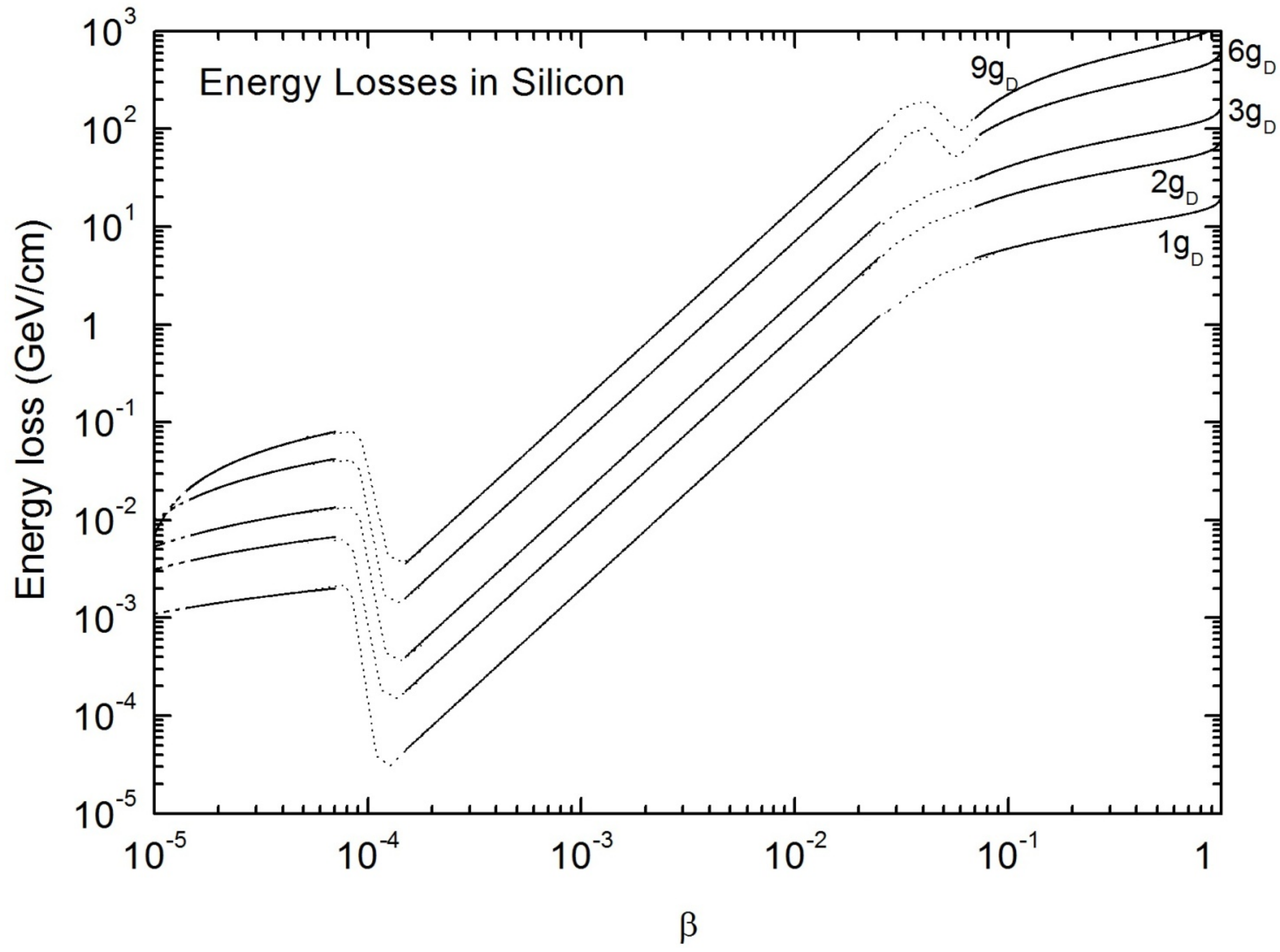
Energy loss in Iron



Energy loss in Copper



Energy loss in Silicon



Restricted Energy loss in NTDs (Makrofol)

- Nuclear-track detectors (NTDs) are sensitive to the fraction of the energy loss restricted to a cylinder of radius < 10 nm along the particle track.

→ mainly due to short delta rays.

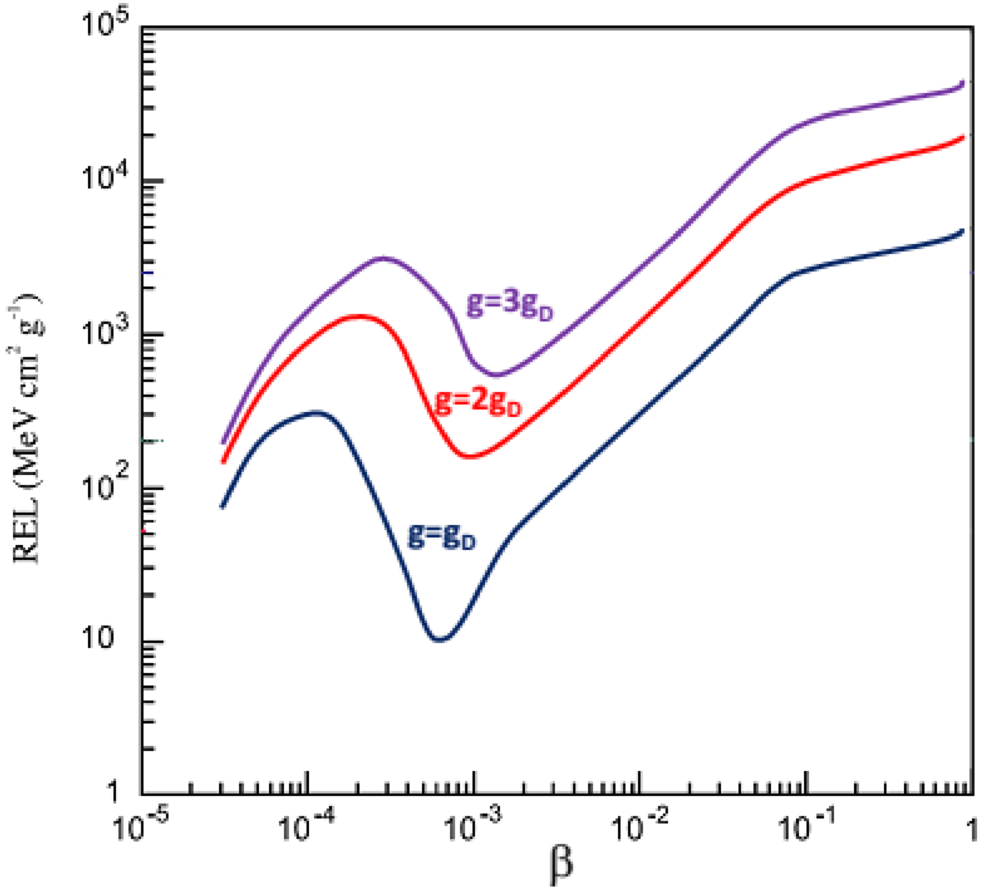
- $\beta > 0.1$

$$REL = \left(-\frac{dE}{dx}\right)_{E<T_{max}} = K\frac{z^2}{\beta^2}\frac{Z}{A}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

$$T_{max} = \frac{2m_e c^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}.$$

- $\beta < 0.05$ REL = - $(dE/dx)_{ETot}$

Restricted Energy loss in NTDs (Makrofol)



Thank you !

Restricted Energy loss in NTDs (Makrofol)