ANALIZA IONSKIH TRAGOVA

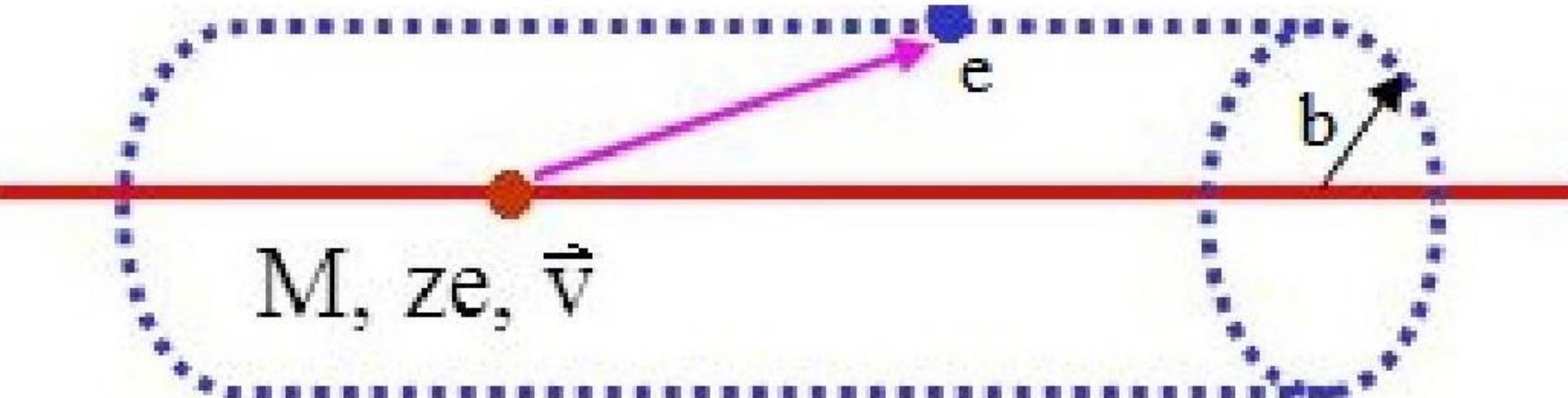
U $SrTiO_3$, TiO_2 I ODABRANIM PIROKLORIMA

PROLAZAK NABIJENE ČESTICE

- teške, lake... (elektron)
- neelastična rasp. na elekt. i elast. na jezgrama (gubitak, odmak) -> ostalo zanemarujemo (teške 10-ak Mev-a)
- statističnost pojava (neto efekt) -> Ruth. (klas.) i ne Ruth. presjeci (kvantni, nukl. reak.)
- srednji gubitak -> zaustavna moć dE/dx (računamo)

INTERAKCIJA TEŠKE NABIJENE ČESTICE S ATOMSKIM ELEKTRONIMA

- elektron slobodan i početno miruje, a tokom interakcije s teškom nabijenom česticom vrlo malo pomakne pa interakciju možemo gledati na njegovom početnom položaju. Za projektil uzimamo da se ne odmiče od početnog smjera pošto je M >> m



KLASIČNI (BOHROV) IZRAZ

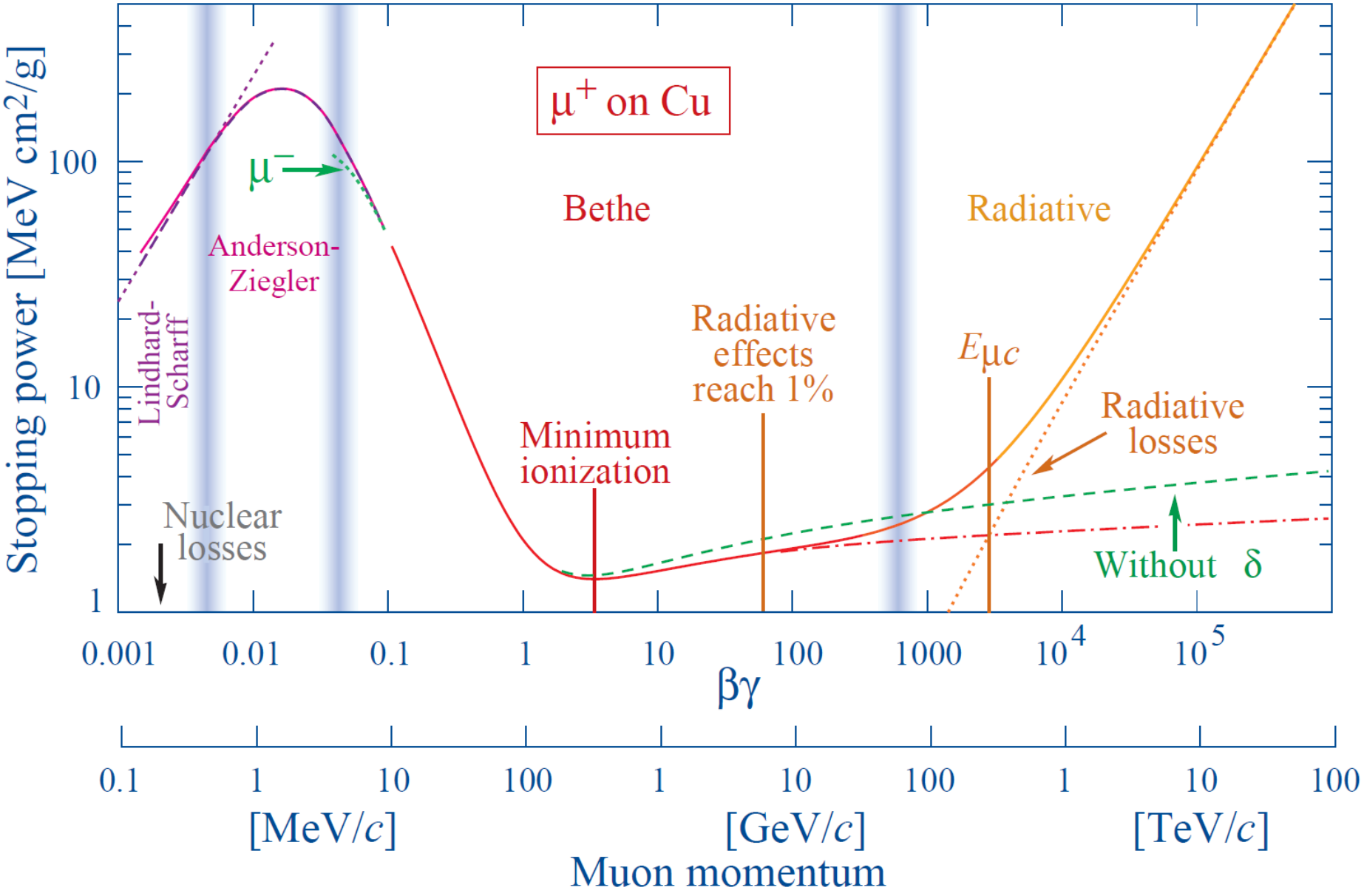
$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} N_e ln \frac{\gamma^2 m v^3}{z e^2 \bar{\nu}}.$$

- integriranje u konačnim vrijednostima (min->čeoni sudar, max->adijabatska invarijanta)
- ova formula predstavlja dovoljno dobar prikaz gubitka energije za vrlo teške čestice kao što su α-čestice i teške jezgre no za lakše kao što su protoni nije dostatna zbog kvantnih efekata

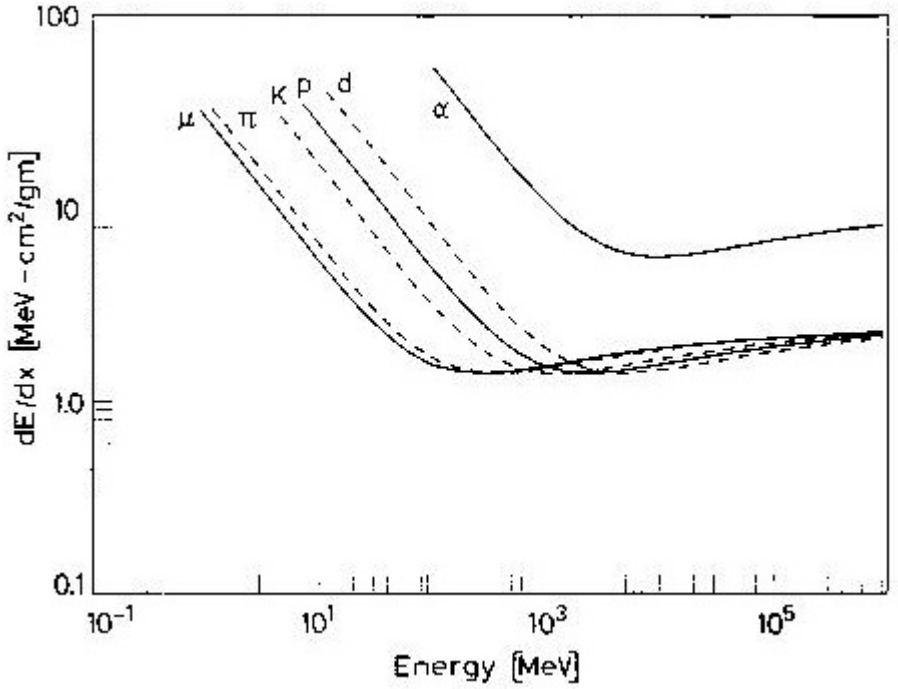
BETHE-BLOCH

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[ln \left(\frac{2m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right.$$

- uključuje kvantne efekte
- parametrizacija izmjene energije preko izmjene impulsa (udarni parametar)
- density efekt -> polarizacija (energija, gustoća)
- shell -> više efekata (odnos brzina)
- ostalo zanemarujemo (iznimka uhvat elektrona kod teških iona na malim brzinama, sve ostalo ~1%)

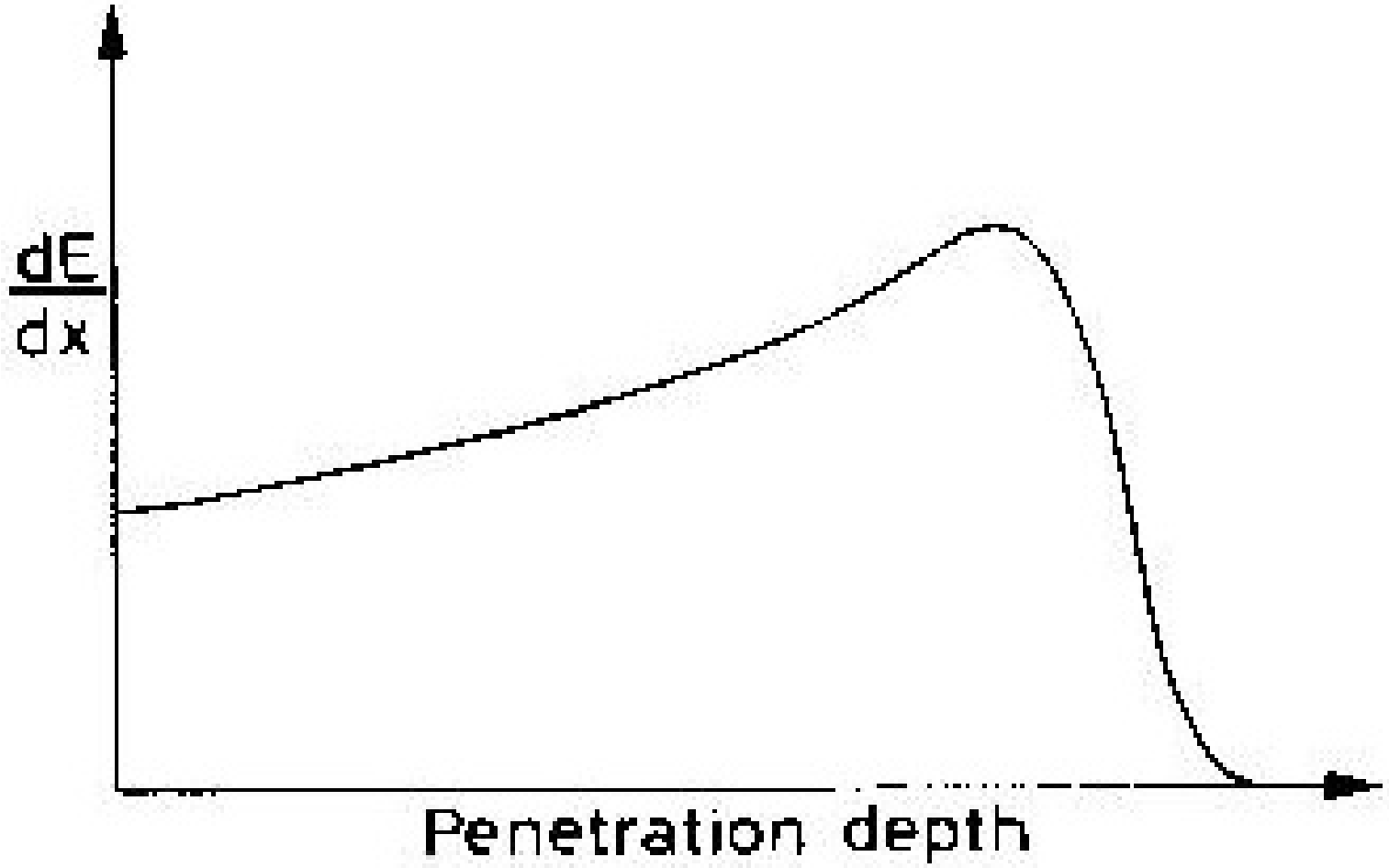

μ+ on Cu
μ−
Bethe
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Radiative
effects
reach 1%
Eμc
Minimum
ionization
Radiative
losses
Nuclear
losses
Without δ
Stopping power [MeV cm2/g]
100
10
1
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

ENERGIJSKA OVISNOST



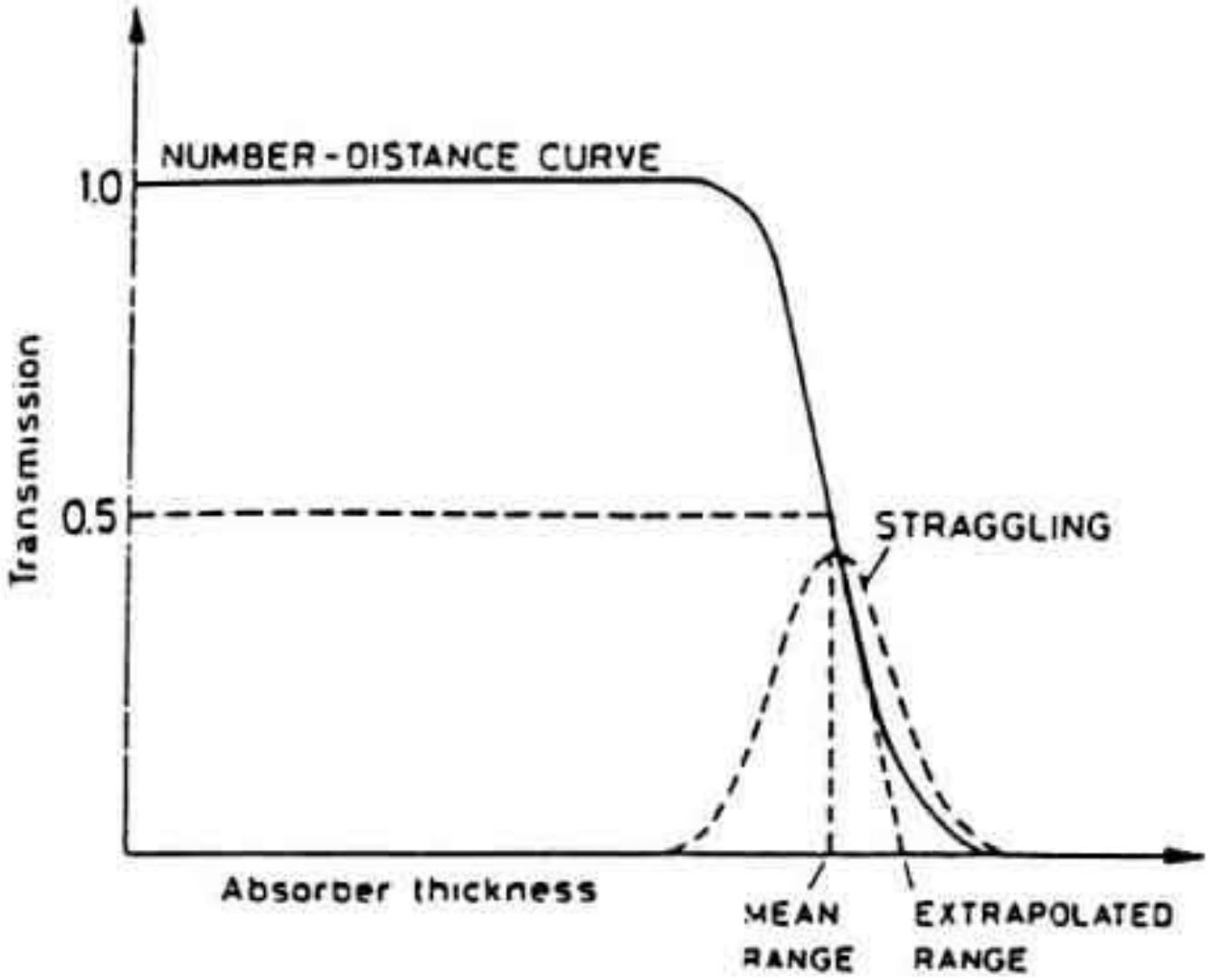
- 1/β^2, minimum ionizacije 0.96c (naboj)
- logaritamski porast, density ograničenje

BRAGGOVA KRIVULJA

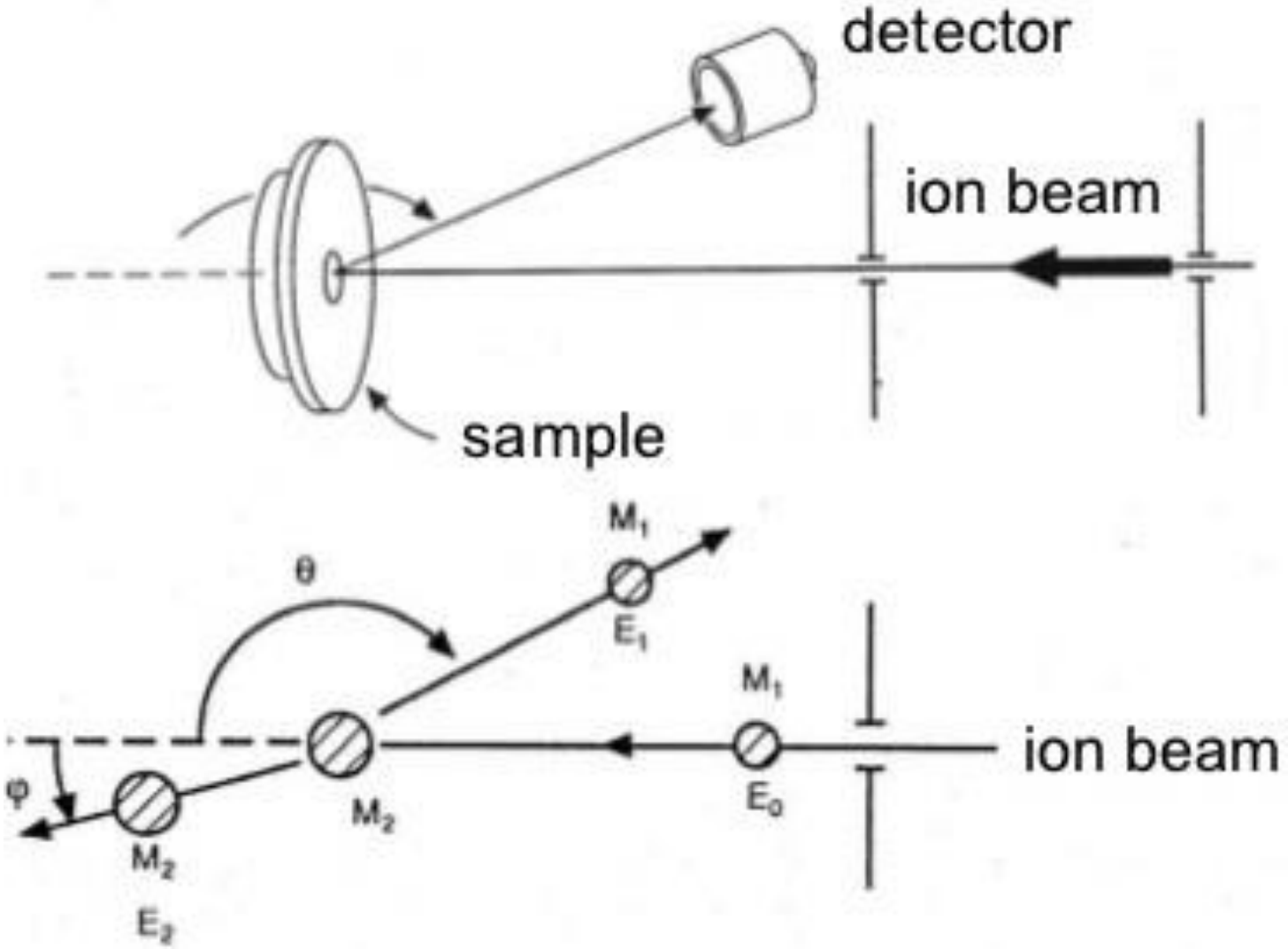


OGRANIČENJA

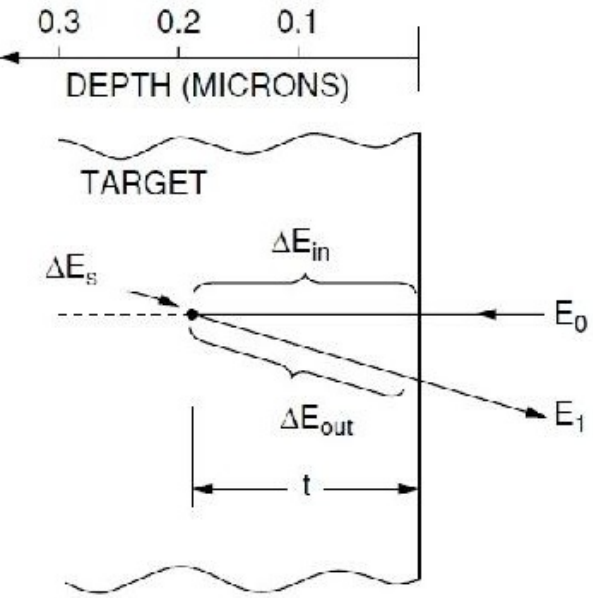
- dobro za “elementarne čestice”, α-čestice i lakše jezgre
- brzine do $\beta \approx 0.1$
- teže do $Z \approx 56$ -> efektivni naboj (radijacijski efekti)
- kanaliranje ($\approx 1°$ za $\beta \approx 0.1$, obrnuto proporcionalno s energijom)


NUMBER - DISTANCE CURVE
1.0
0.5
Transmission
STRAGGLING
Absorber thickness
MEAN RANGE
EXTRAPOLATED RANGE

RBS



$$K = \frac{E_1}{E_0} = \left[\frac{\left(M_2^2 - M_1^2 \sin^2 \theta \right)^{1/2} + M_1 \cos \theta}{M_1 + M_2} \right]^2$$



- iz spektra unazad raspšenih iona koji nam govori o broju i energiji detektiranih iona možemo rekonstruirati elementarni sastav uzorka i dubinske profile u materijalu
- elementarni sastav saznajemo iz spektra jer sudari s različitim jezgrama razultiraju različitim gubitkom energije ulaznog iona određene kinematičkim faktorom dok se dubinski profil saznaje poznavajući zaustavnu moć iona u uzorku

$$\Delta E_{in} \simeq \left. \frac{dE}{dx} \right|_{E_0} \cdot t$$

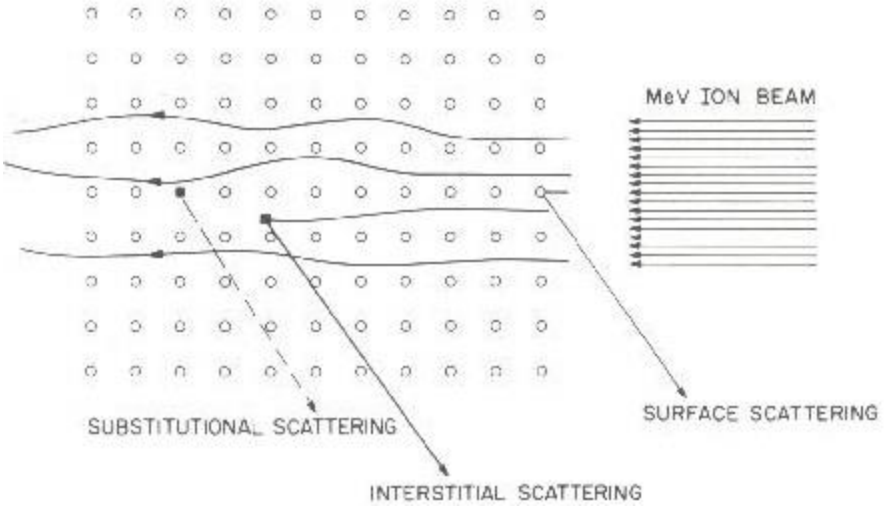
$$E_t = E_0 - \Delta E_{in}$$

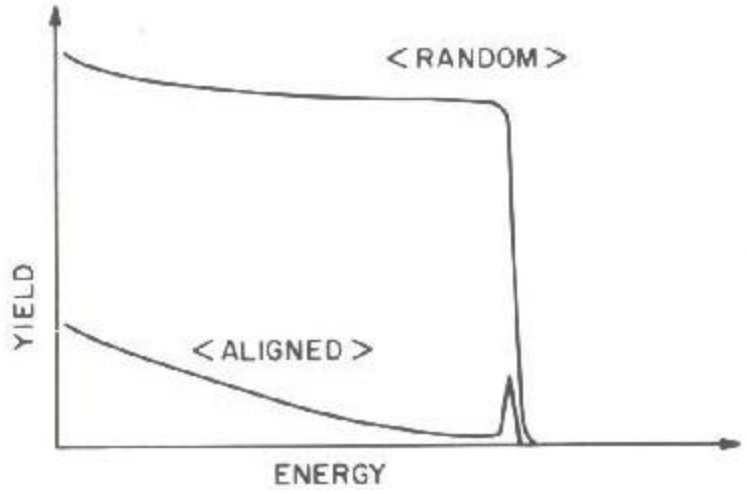
$$\Delta E_s = \left(1 - K\right) E_t$$

$$\Delta E_{out} \simeq \left. \frac{dE}{dx} \right|_{E_1} \cdot \frac{t}{\cos \theta}$$

RBS/c

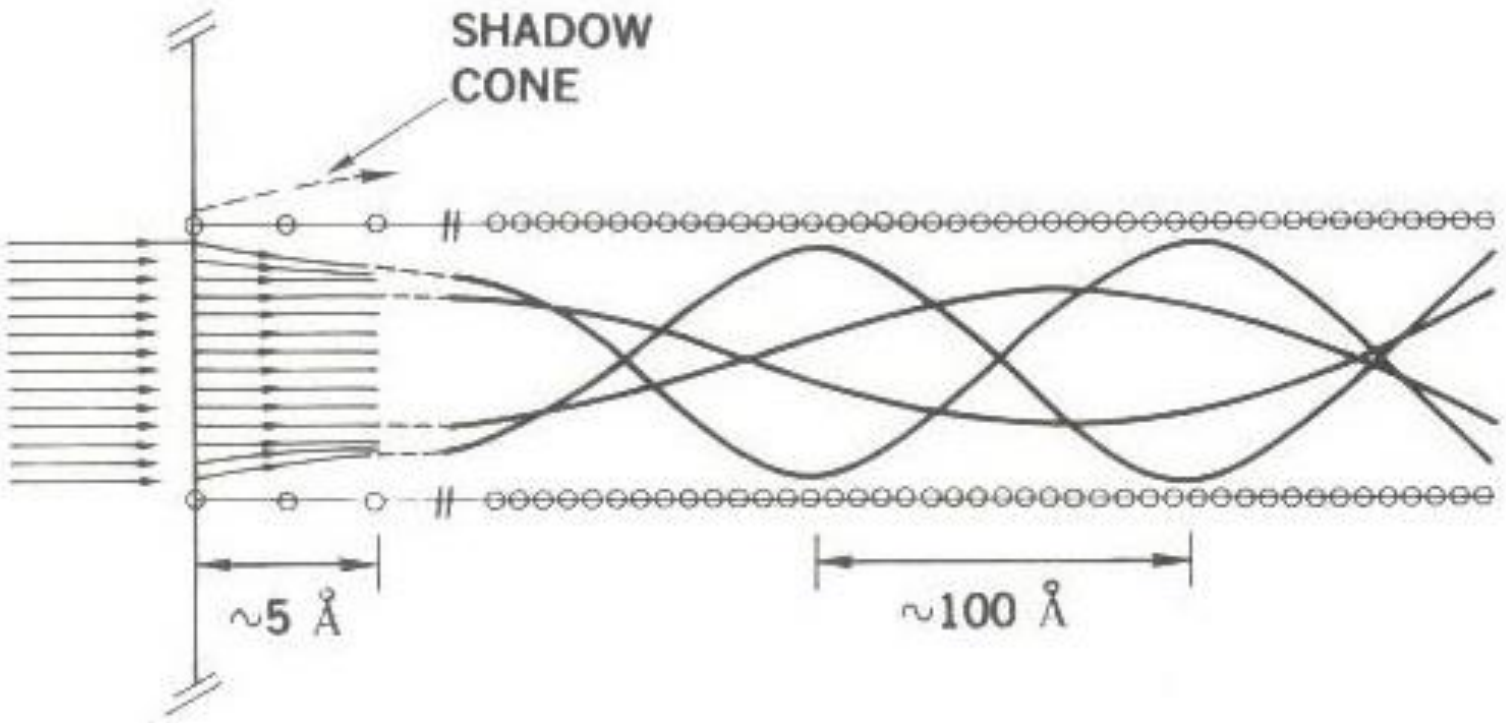
- poravnanje kristalne osi -> kanaliranje iona



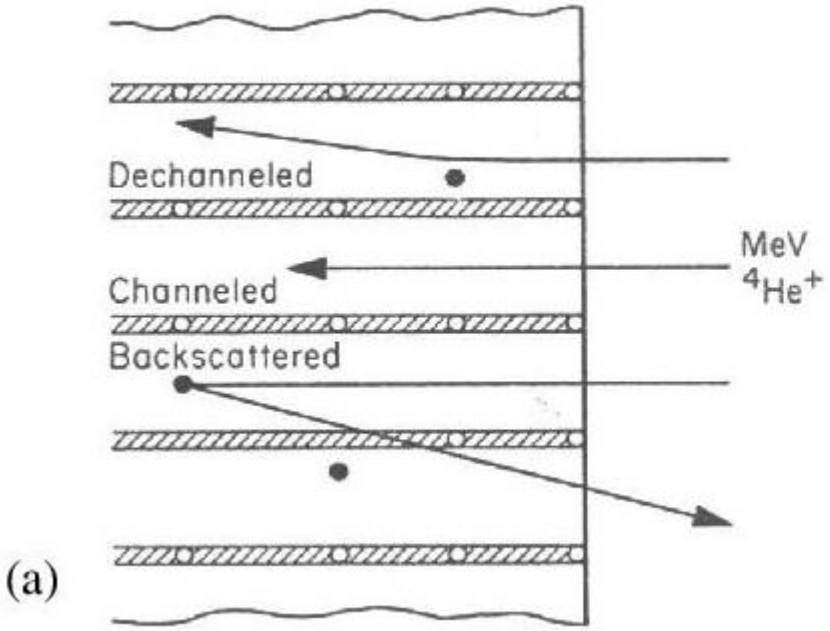


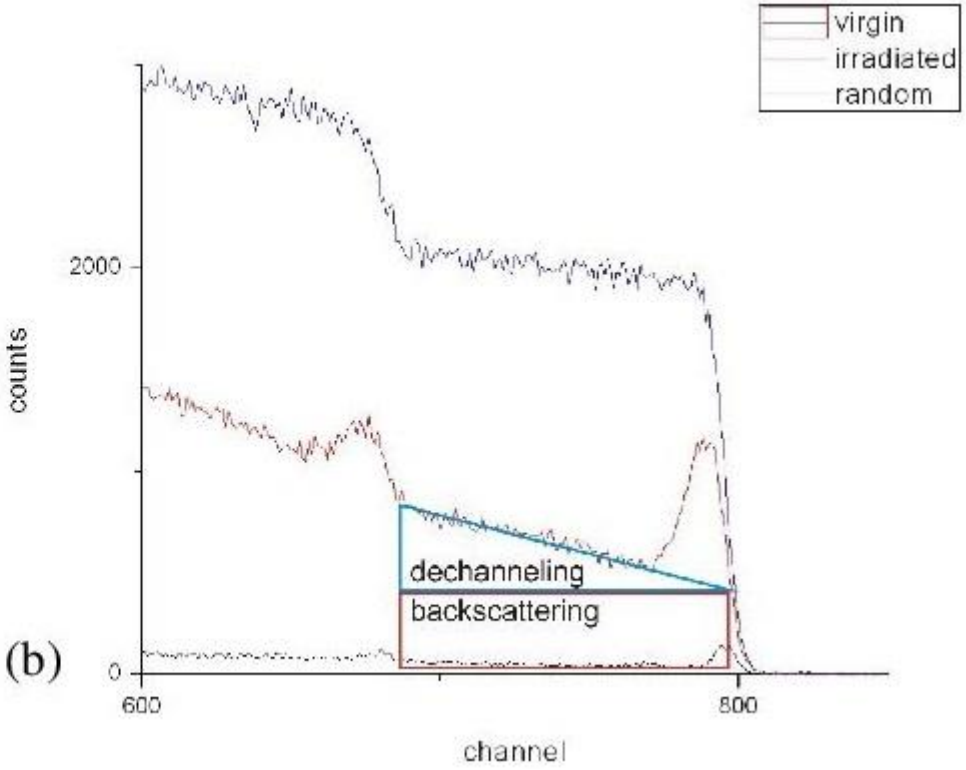
- <u>monokristalinični uzorak</u>

SMANJENJE BROJA DOGAĐAJA



DOPRINOSI RASPRŠENJU I UČINAK NA SPEKTAR





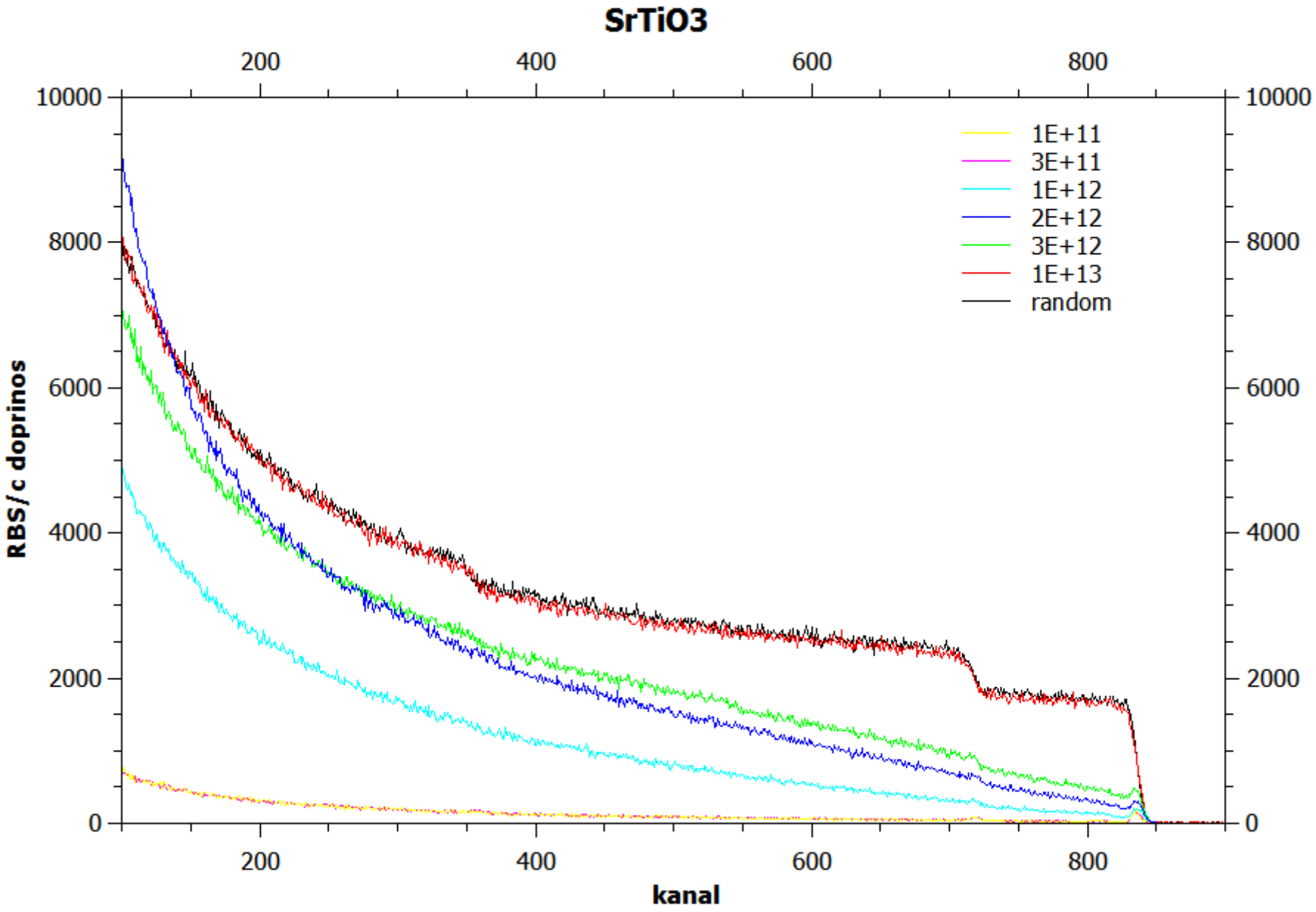
$$F_d = \frac{\chi_{irrad} - \chi_{virgin}}{\chi_{random} - \chi_{virgin}}$$

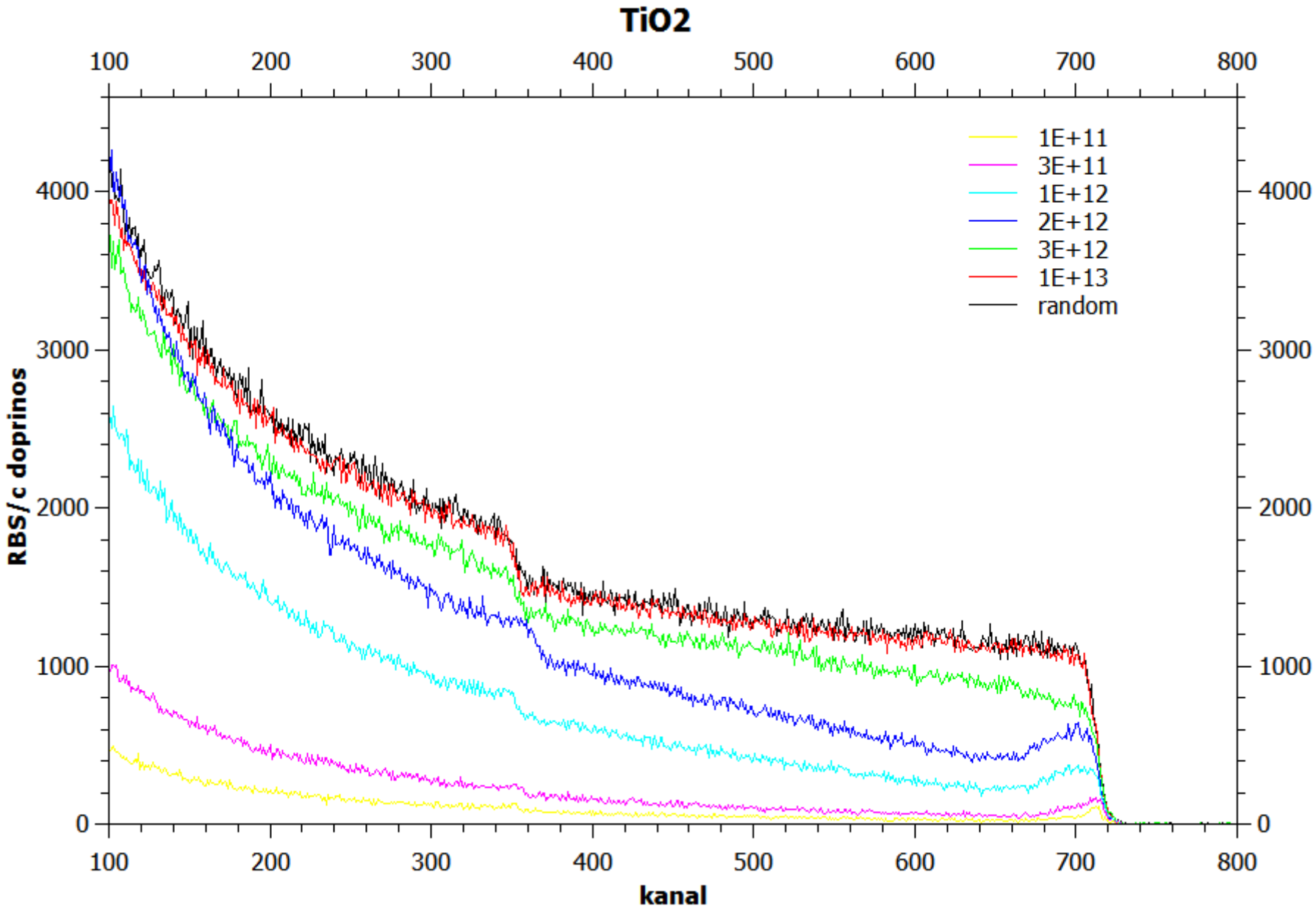
$$F_d = \alpha(1 - e^{-R^2 \pi \Phi})$$

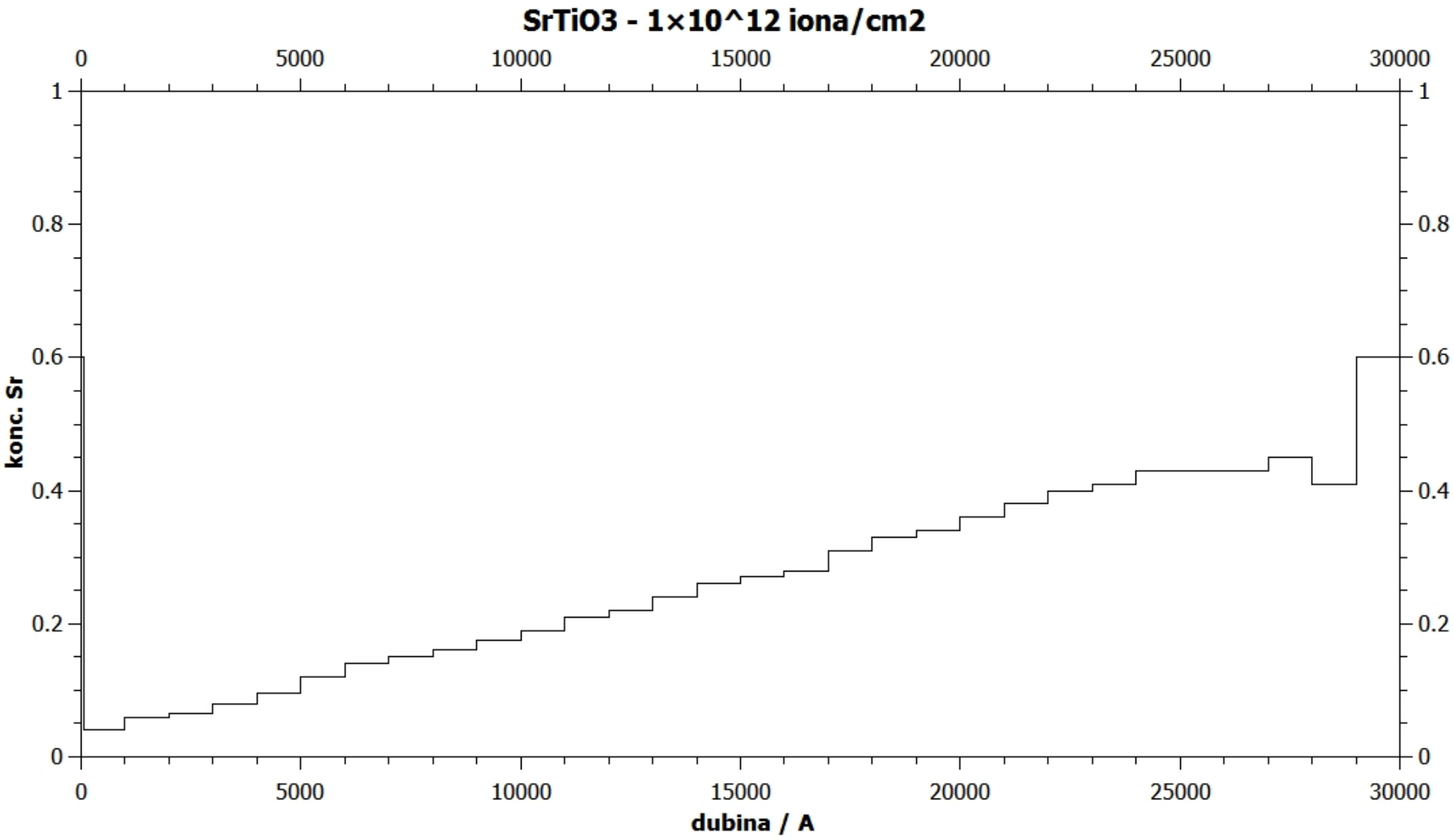
EKSPERIMENTALNI POSTAV

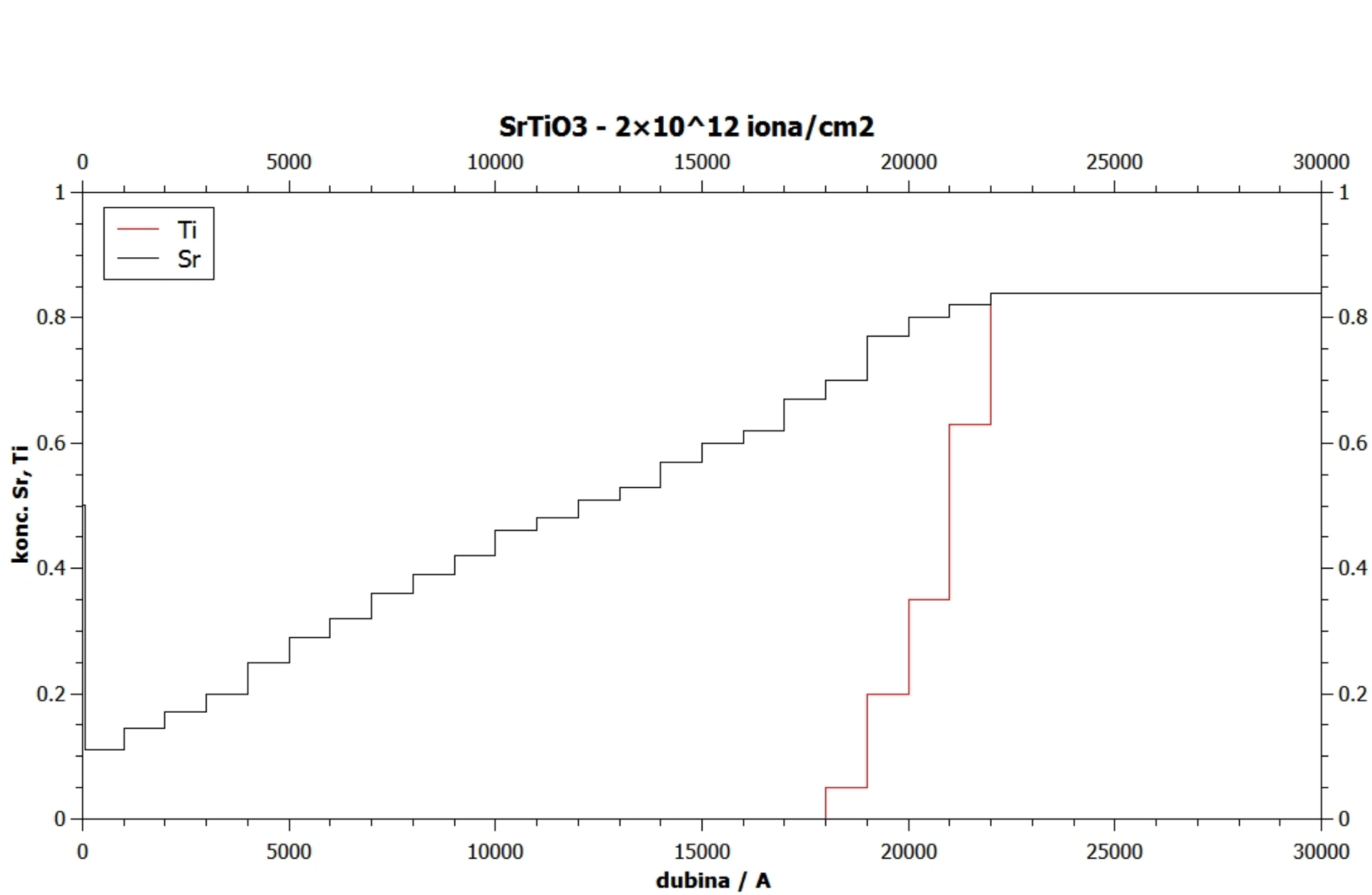
- SRTIO3 (100) i TIO2 (001) 5×5 mm2
- 92 MeV Xe23+ pod 6° na kristalnu os
- Analiza s 1.7 MeV He i SSB detektorom pod 170°
- SRIM,RBX

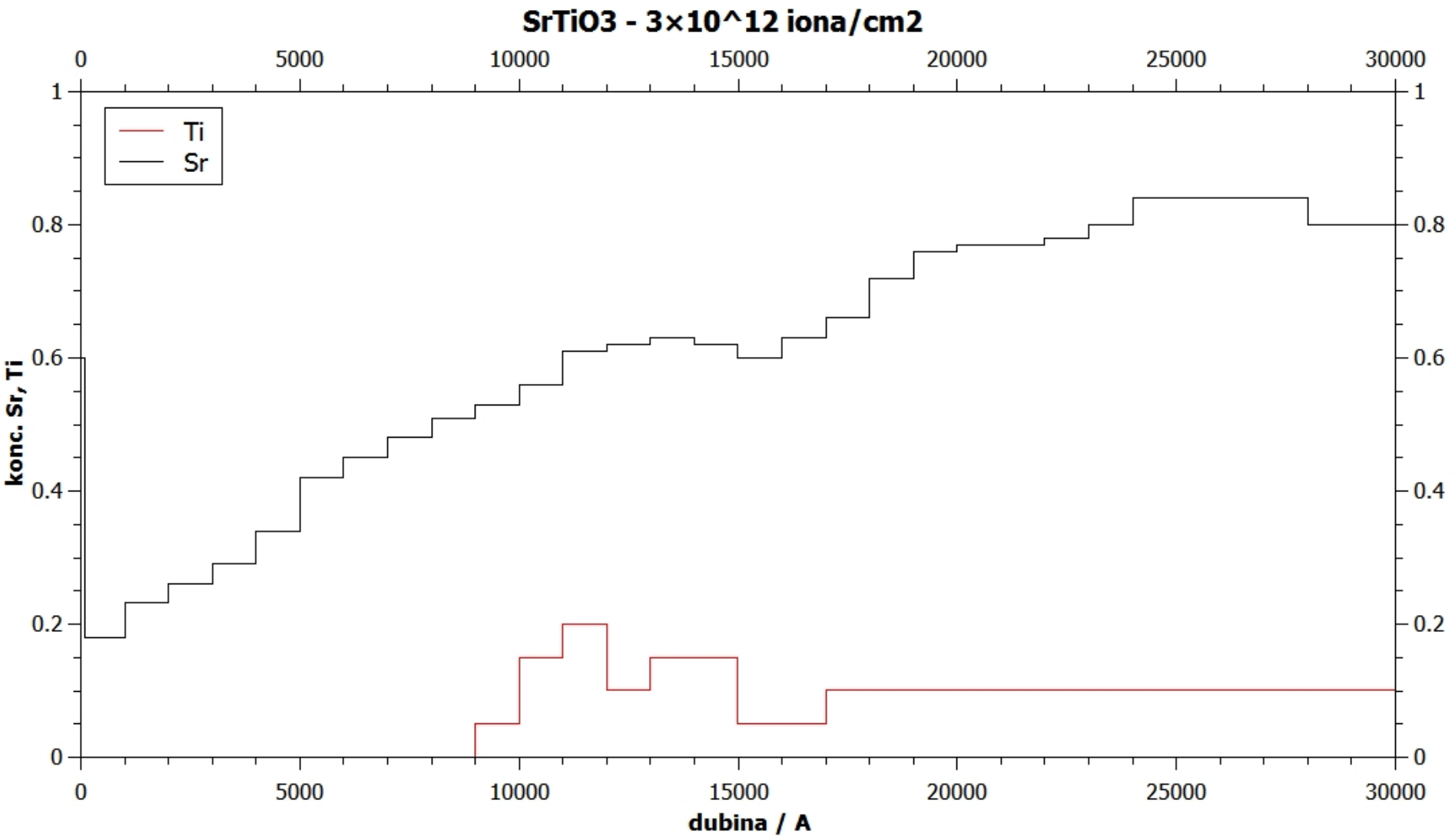
Electronic stopping S_e (keV nm^{-1})	Nuclear stopping S_n (keV nm^{-1})	Range (μm)
20.91	0.18	7.73
21.06	0.16	7.92

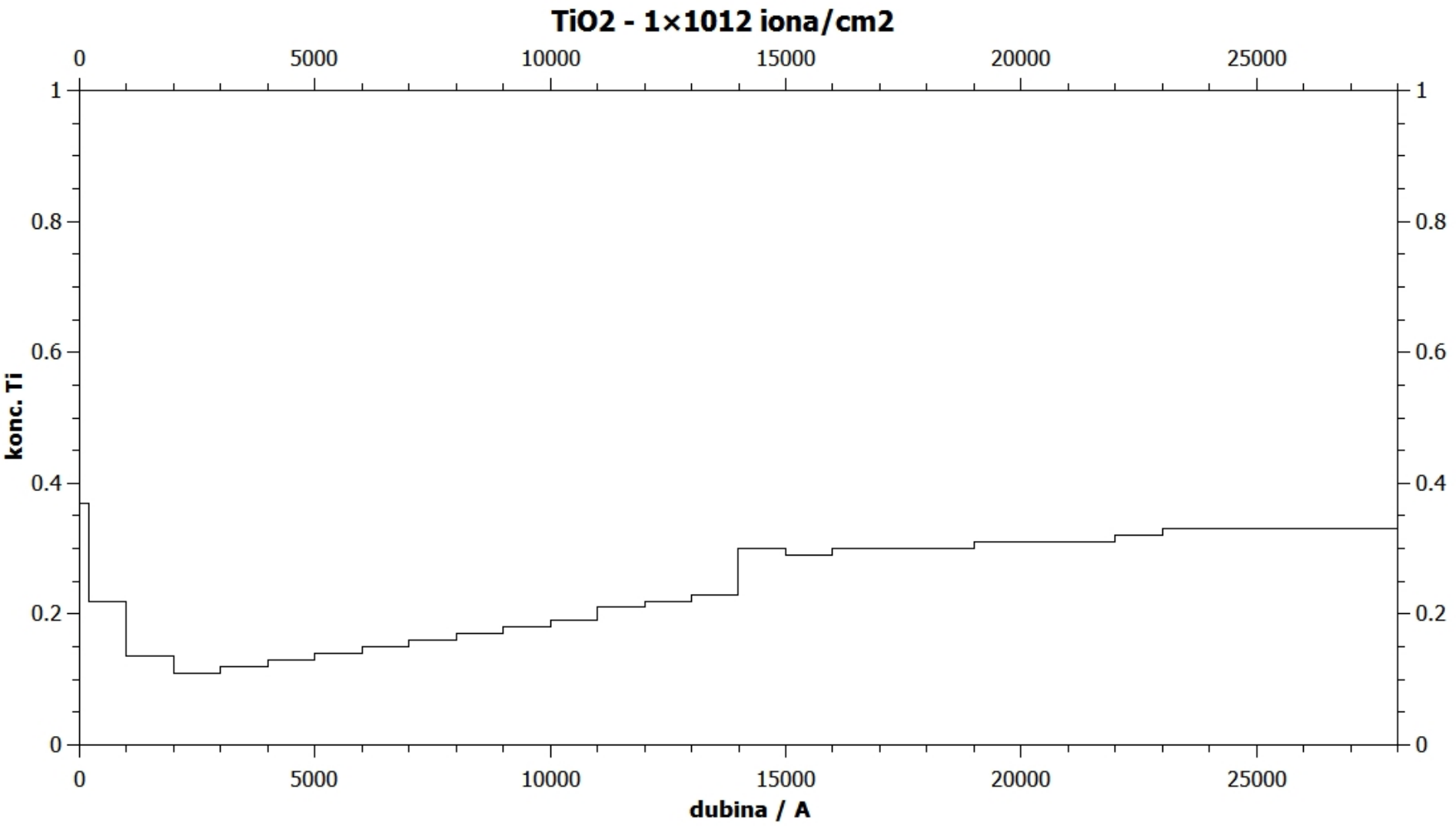

SrTiO3
200
400
600
800
10000
8000
6000
4000
2000
0
RBS/c doprinos
kanal
1E+11
3E+11
1E+12
2E+12
3E+12
1E+13
random

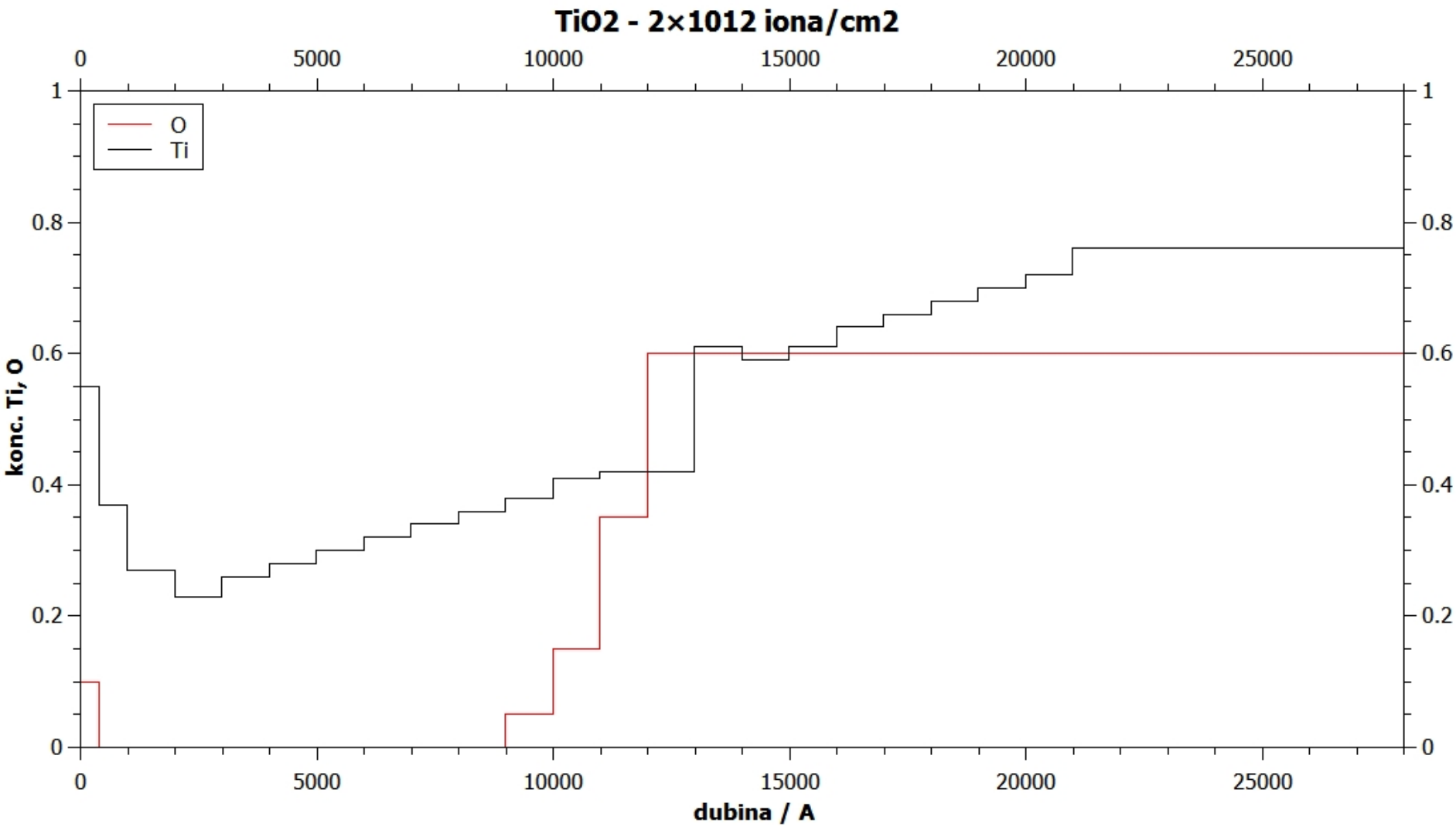

TiO2
100
200
300
400
500
600
700
800
4000
3000
2000
1000
0
RBS/c doprinos
kanal
1E+11
3E+11
1E+12
2E+12
3E+12
1E+13
random

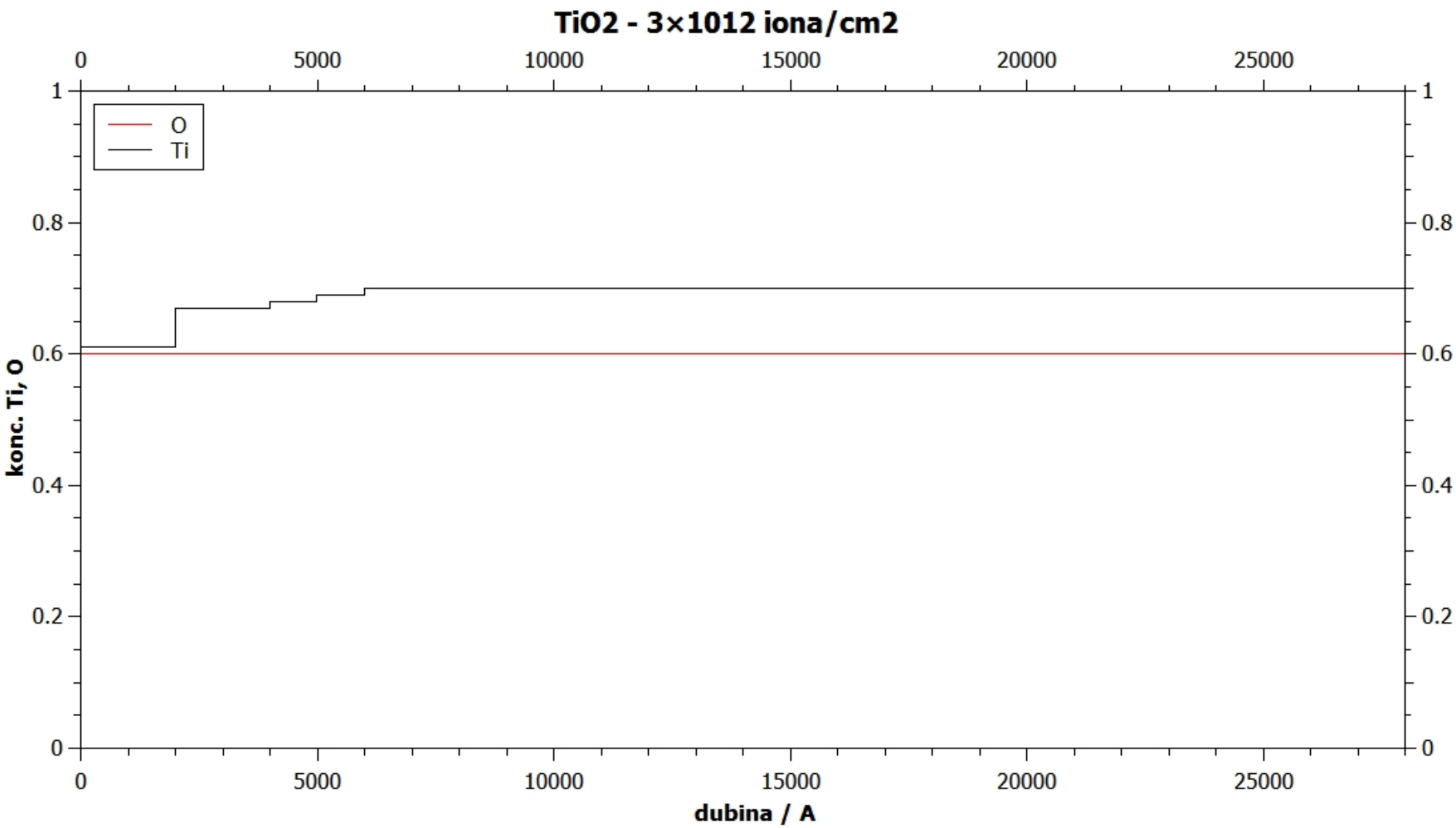

SrTiO3 - 1×10^12 iona/cm2
0
5000
10000
15000
20000
25000
30000
1
0.8
0.6
0.4
0.2
0
konc. Sr
dubina / A


SrTiO3 - 2×10^12 iona/cm2
Ti
Sr
konc. Sr, Ti
dubina / A
0
5000
10000
15000
20000
25000
30000
0
0.2
0.4
0.6
0.8
1


SrTiO3 - 3×10^12 iona/cm2
Ti
Sr
konc. Sr, Ti
dubina / A
0
5000
10000
15000
20000
25000
30000
0.2
0.4
0.6
0.8
1


TiO2 - 1×1012 iona/cm2
0
5000
10000
15000
20000
25000
1
0.8
0.6
0.4
0.2
0
konc. Ti
dubina / A


TiO2 - 2×1012 iona/cm2
O
Ti
konc. Ti, O
dubina / A
0
5000
10000
15000
20000
25000
0.2
0.4
0.6
0.8
1


TiO2 - 3×1012 iona/cm2
0
5000
10000
15000
20000
25000
1
0.8
0.6
0.4
0.2
0
O
Ti
konc. Ti, O
dubina / A

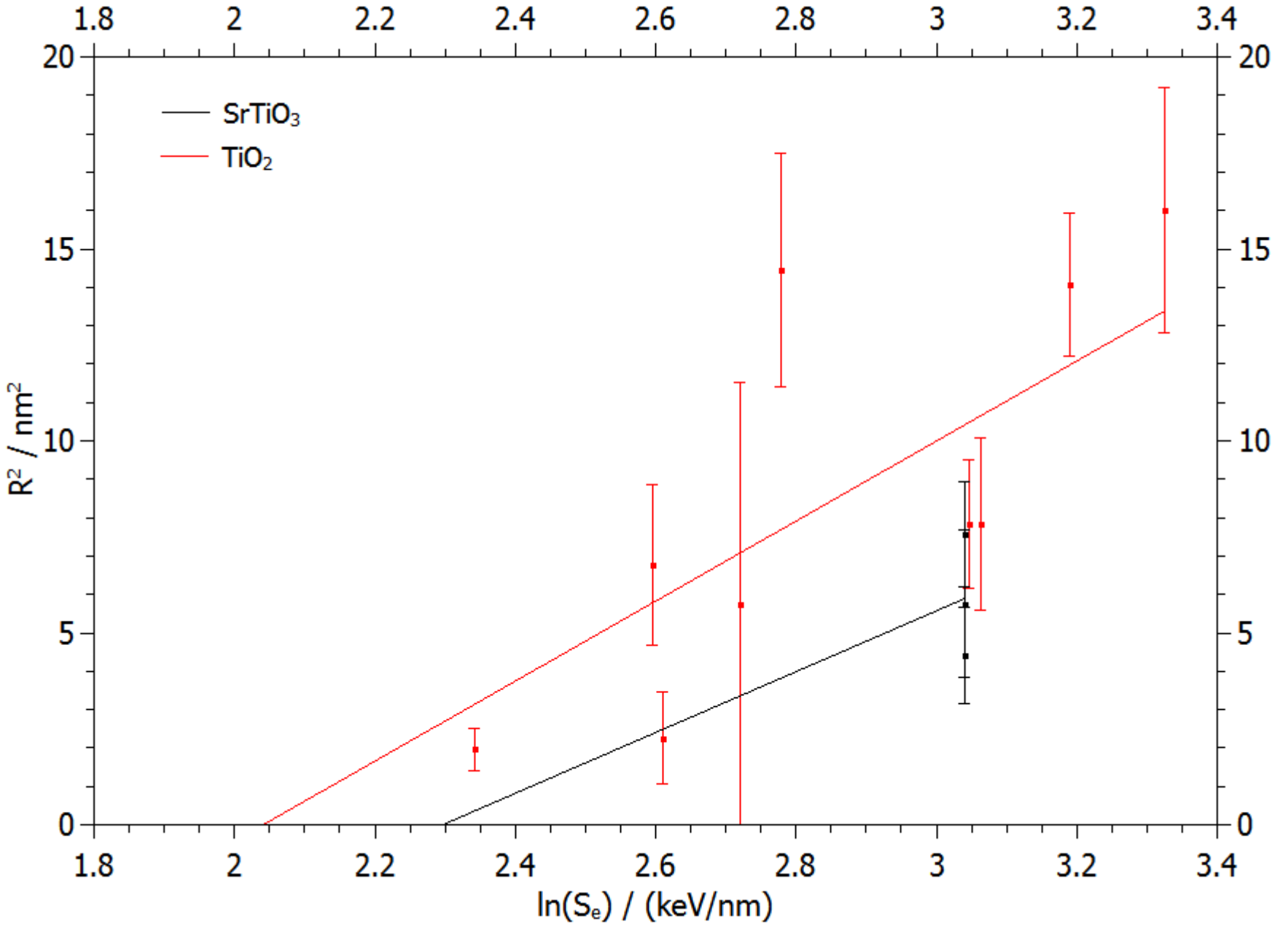
ATSM

$$\Delta T(r,\,t) = \frac{Q}{\pi a^2(t)} e^{-\frac{r^2}{a^2(t)}} \qquad R^2 = a_0^2 ln \frac{S_e}{S_{et}}, \qquad 1 \leq \frac{S_e}{S_{et}} \leq e$$

$$gS_e = \rho c Q + \rho \pi R^2 L \simeq \rho c Q \qquad R^2 = \frac{a_0^2}{e} \frac{S_e}{S_{et}}, \qquad \frac{S_e}{S_{et}} \geq e$$

$$S_{et} = \frac{\rho c \pi a_0^2 \Delta T_m}{g}$$

- a(t=0)=a0 =4.5 nm (0.02-20 MeV/u)
- g (0.17>8MeV/U,0.4<2 MeV/u)

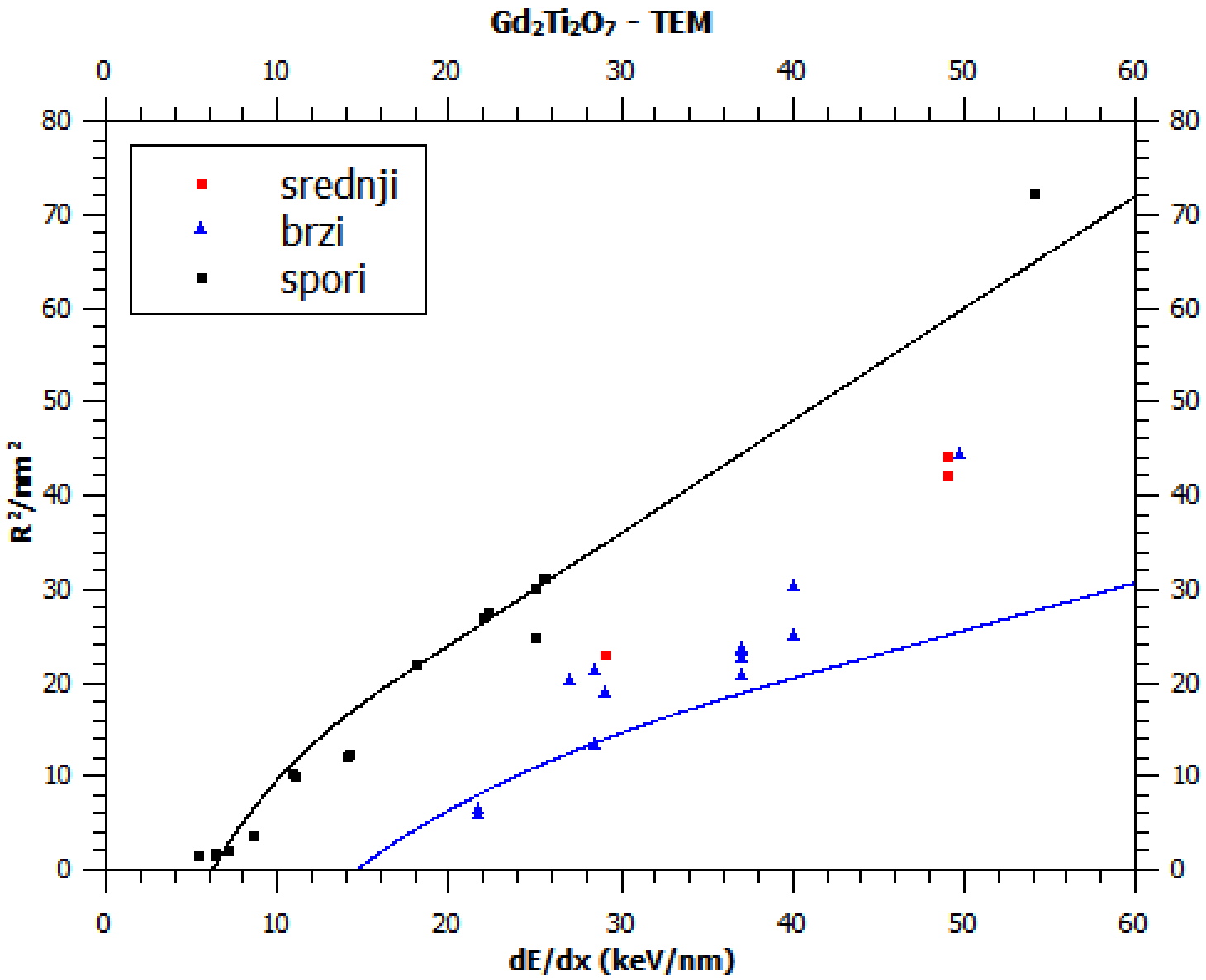

SrTiO3
TiO2
R² / nm²
ln(Se) / (keV/nm)
0
5
10
15
20
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4

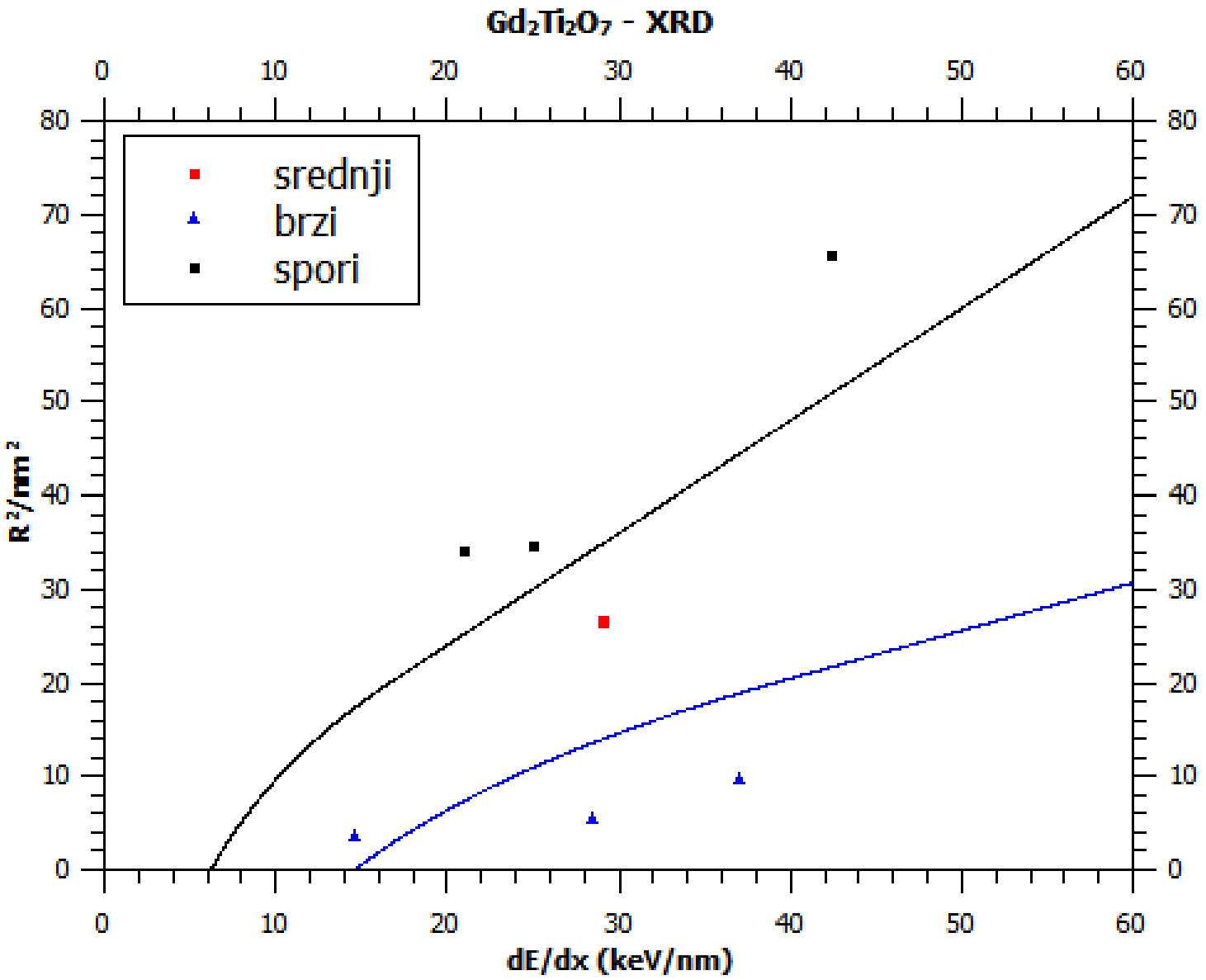
	$SrTiO_3$
Density ρ (g cm^{-3})	5.13
Specific heat capacity c (J g^{-1} K^{-1})	0.68
Melting temperature T_m (°C)	2050
$\rho \times c \times (T_m - RT)$ (J cm^{-3})	7081
Energy band gap E_g (eV)	3.27

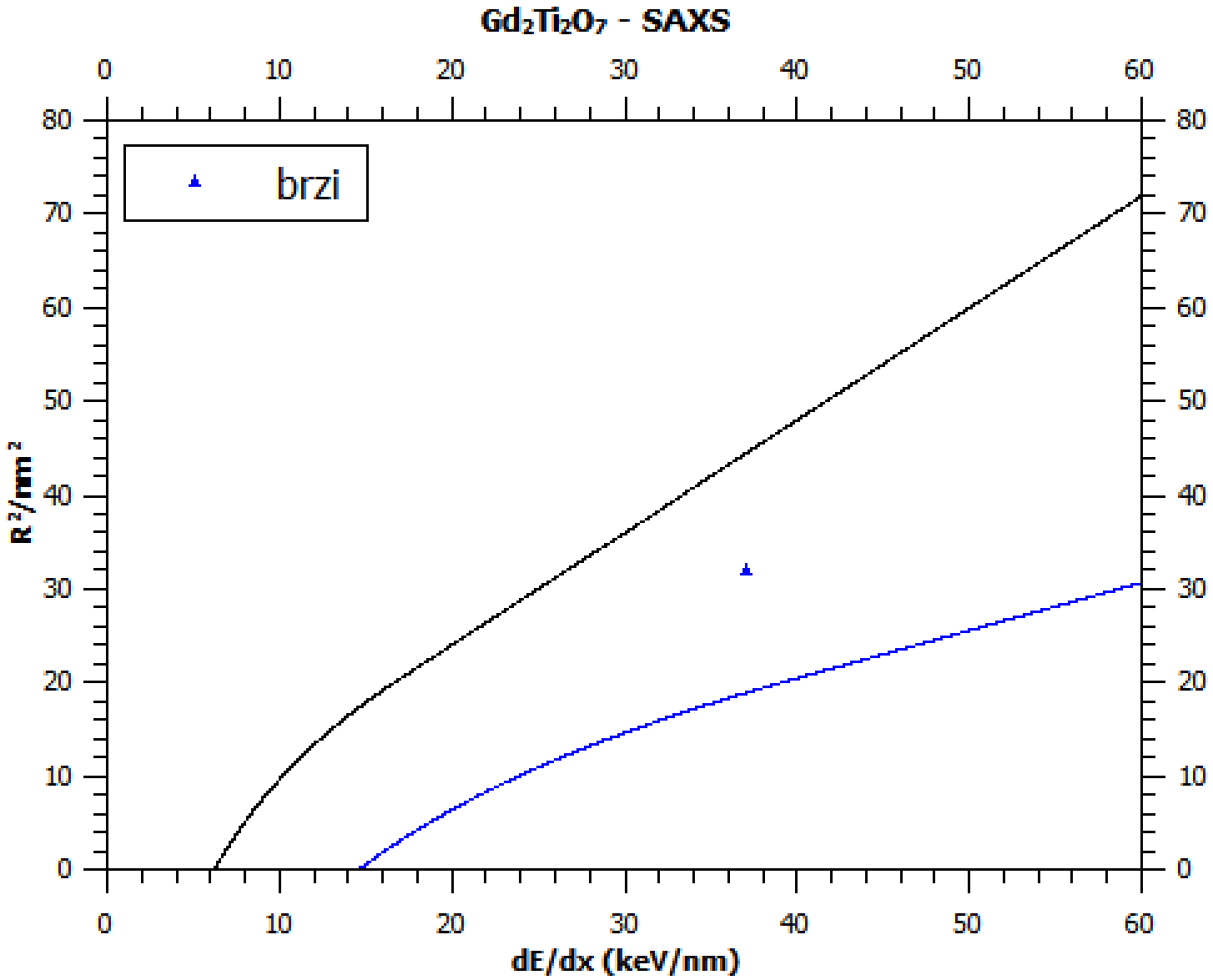
- 2.8 ± 0.2nm za SrTiO 3 i 3.2 ± 0.3nm za TiO 2 (a0)
- 9.44 keV/nm za SrTiO 3 te 10.94 keV/nm za TiO 2 (Set)
- 0.12 za SrTiO3 te 0.13->0.21 za TiO 2 (g)
- “velocity effects” (ne u poluvodičima!)

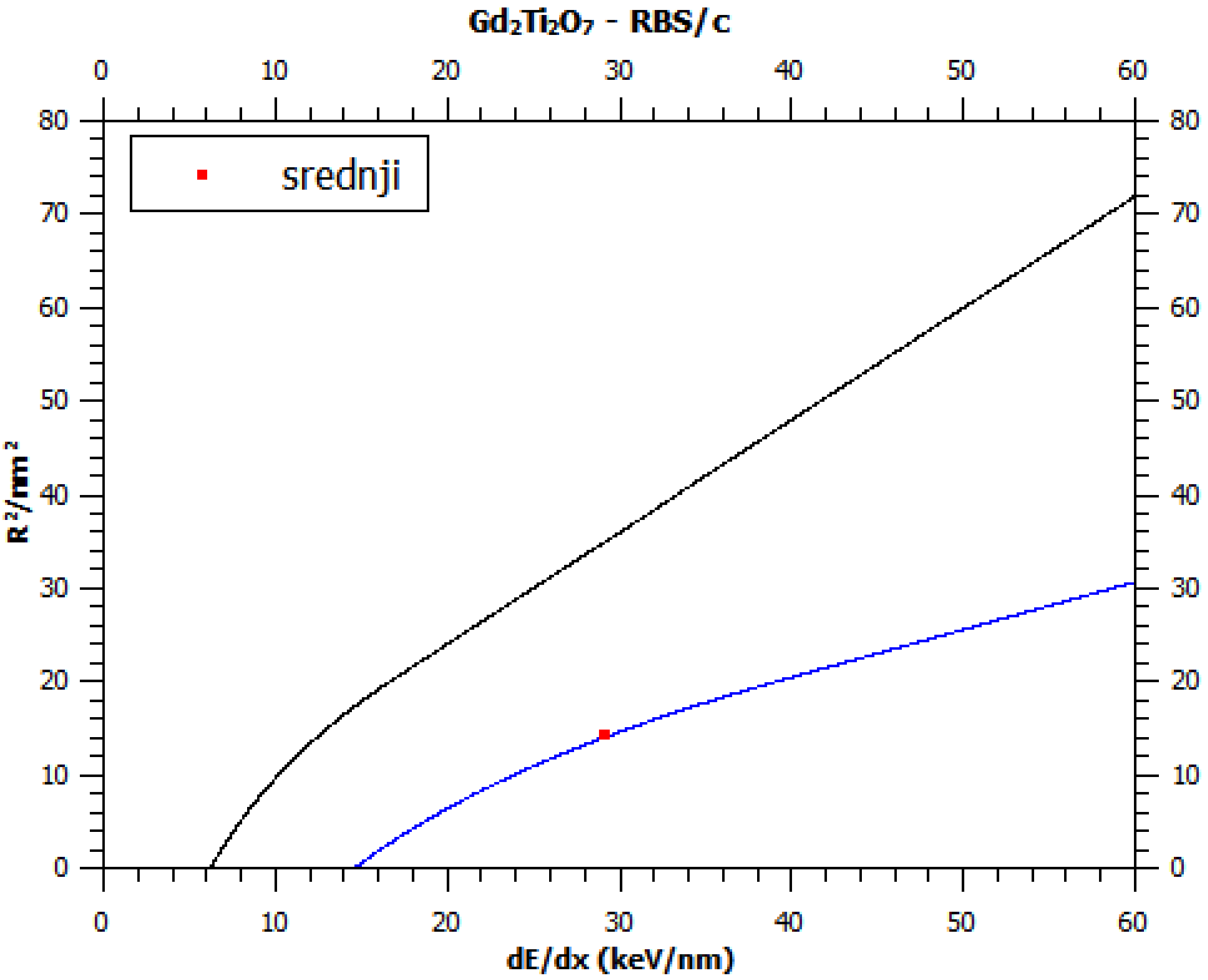
PIROKLORI

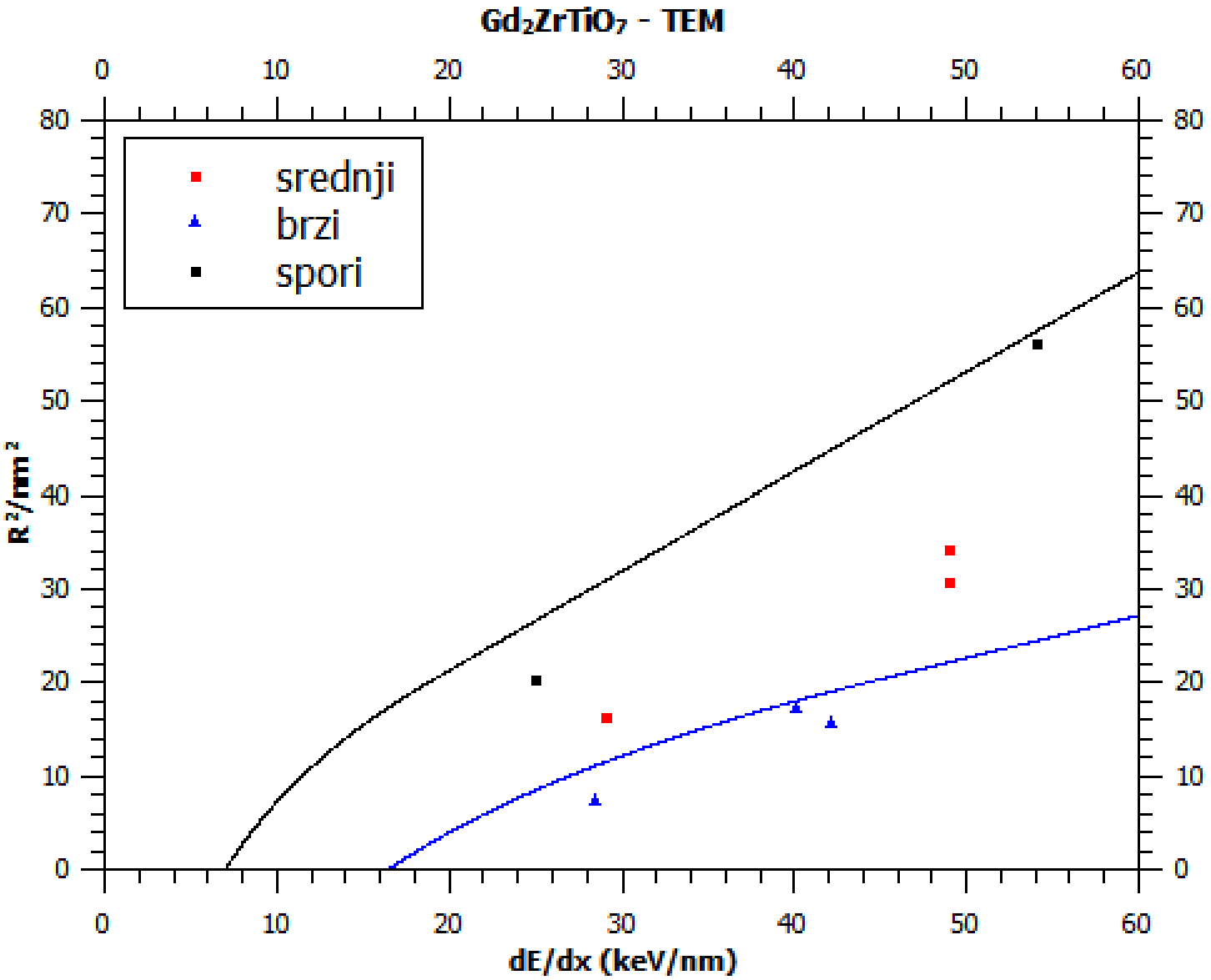
- A2B2O7 ili A2B2O7 -> A,B metali rijetkih zemalja ili prijelazni
- različite fizikalne karakteristike
- skladištenje nuklearnog otpada -> reakcija na fisijske fragmente
- XRD,SAXS,TEM,RBS/c
- Gd2Ti2O7 , Gd2ZrTiO7 , Gd2Zr2O7 , La 2Ti2O7 i Nd2Zr2O7

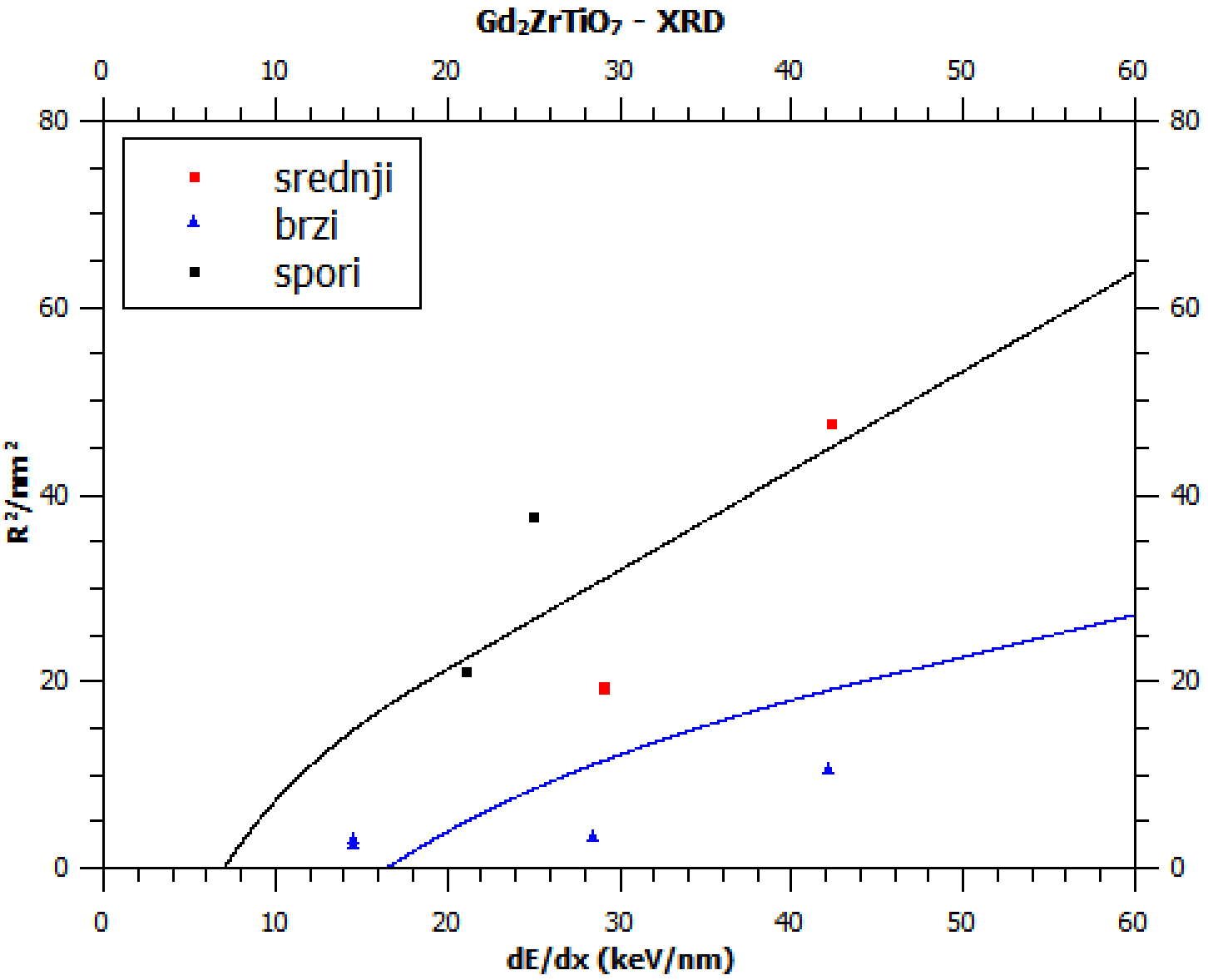

Gd2Ti2O7 - TEM
srednji
brzi
spori
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80

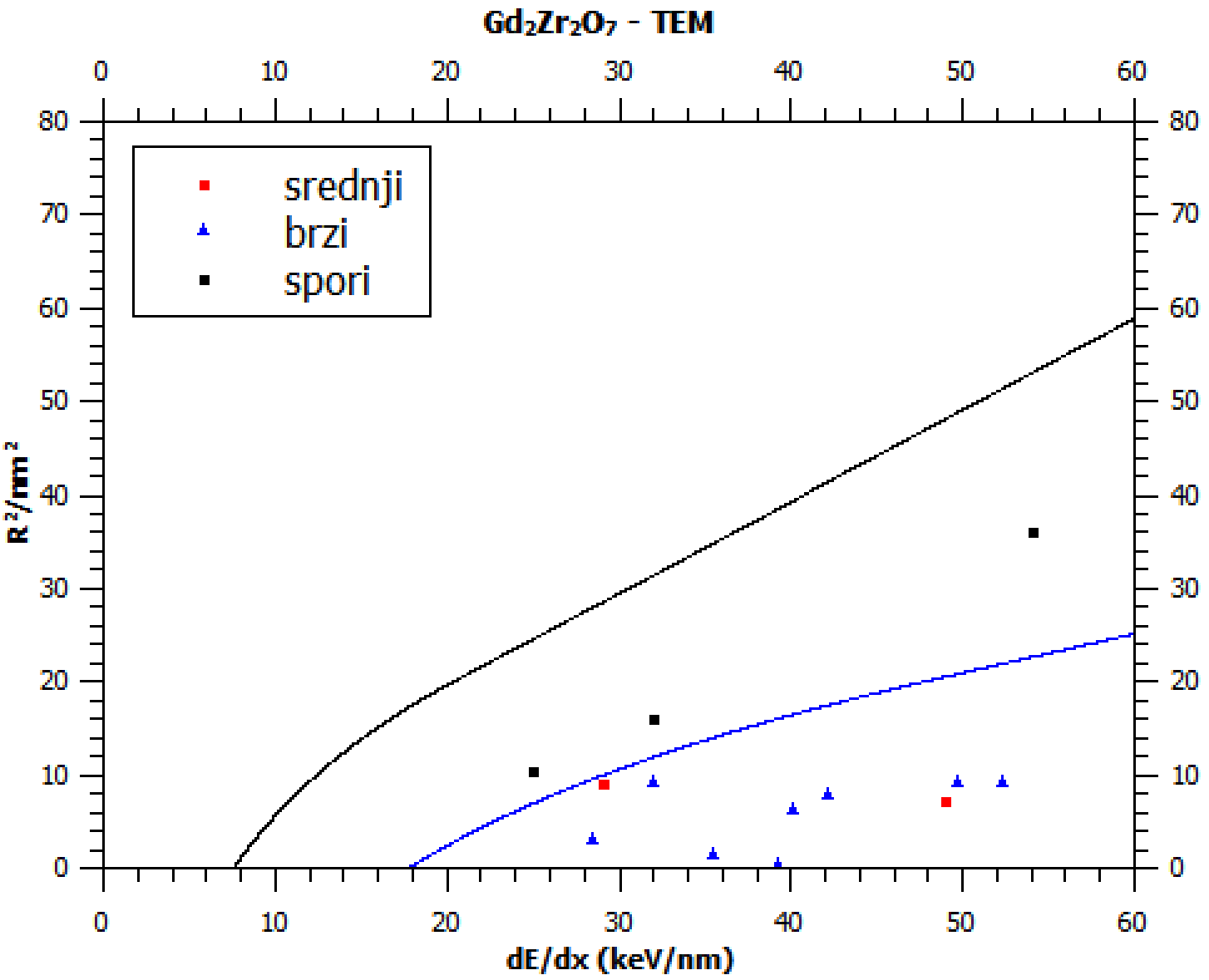

Gd2Ti2O7 - XRD
srednji
brzi
spori
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


Gd2Ti2O7 - SAXS
brzi
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


Gd2Ti2O7 - RBS/c
srednji
R2/nm2
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


Gd2ZrTiO7 - TEM
srednji
brzi
spori
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


Gd2ZrTiO7 - XRD
srednji
brzi
spori
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
80


Gd2Zr2O7 - TEM
srednji
brzi
spori
R2/nm2
dE/dx (keV/nm)
0
10
20
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40
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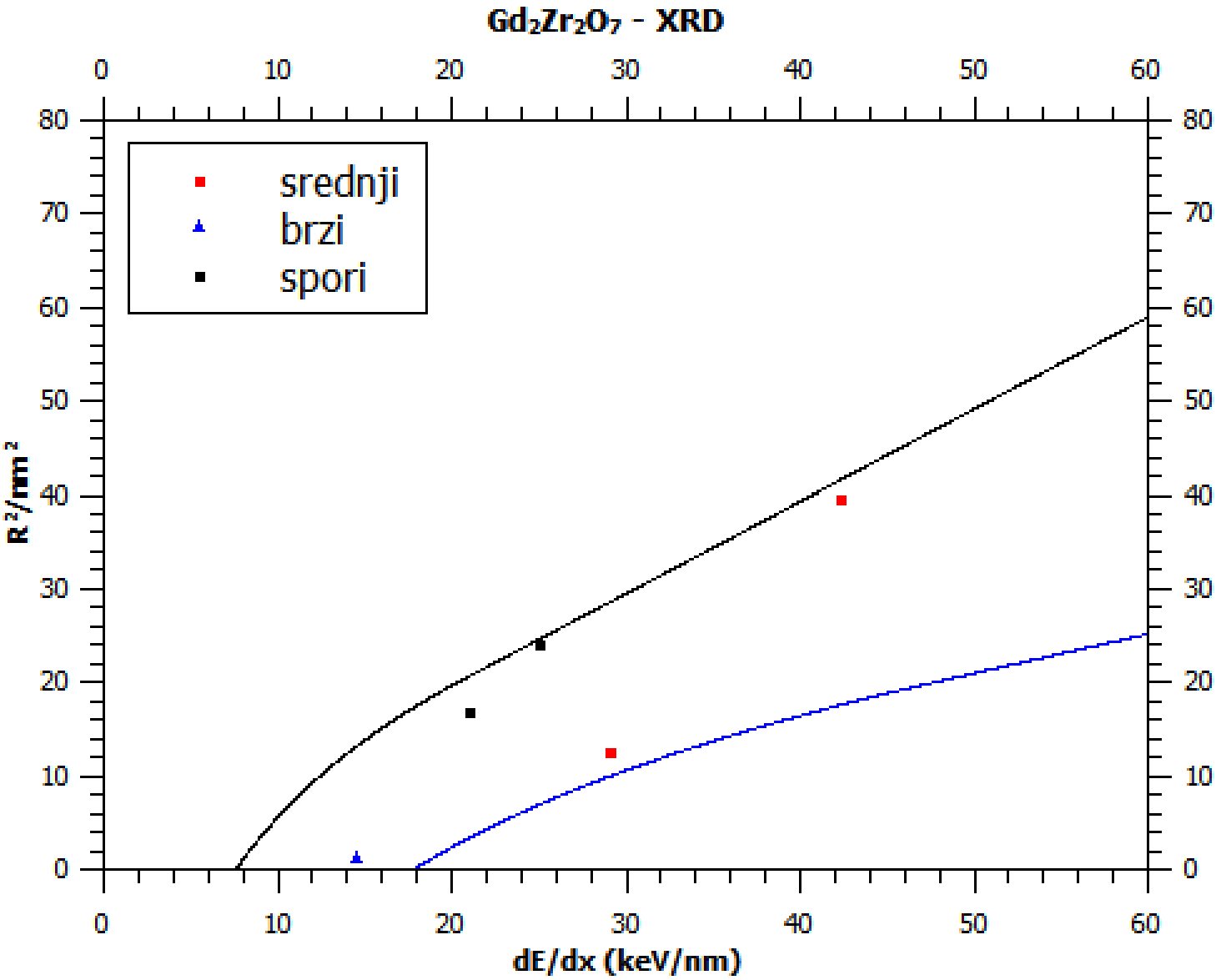
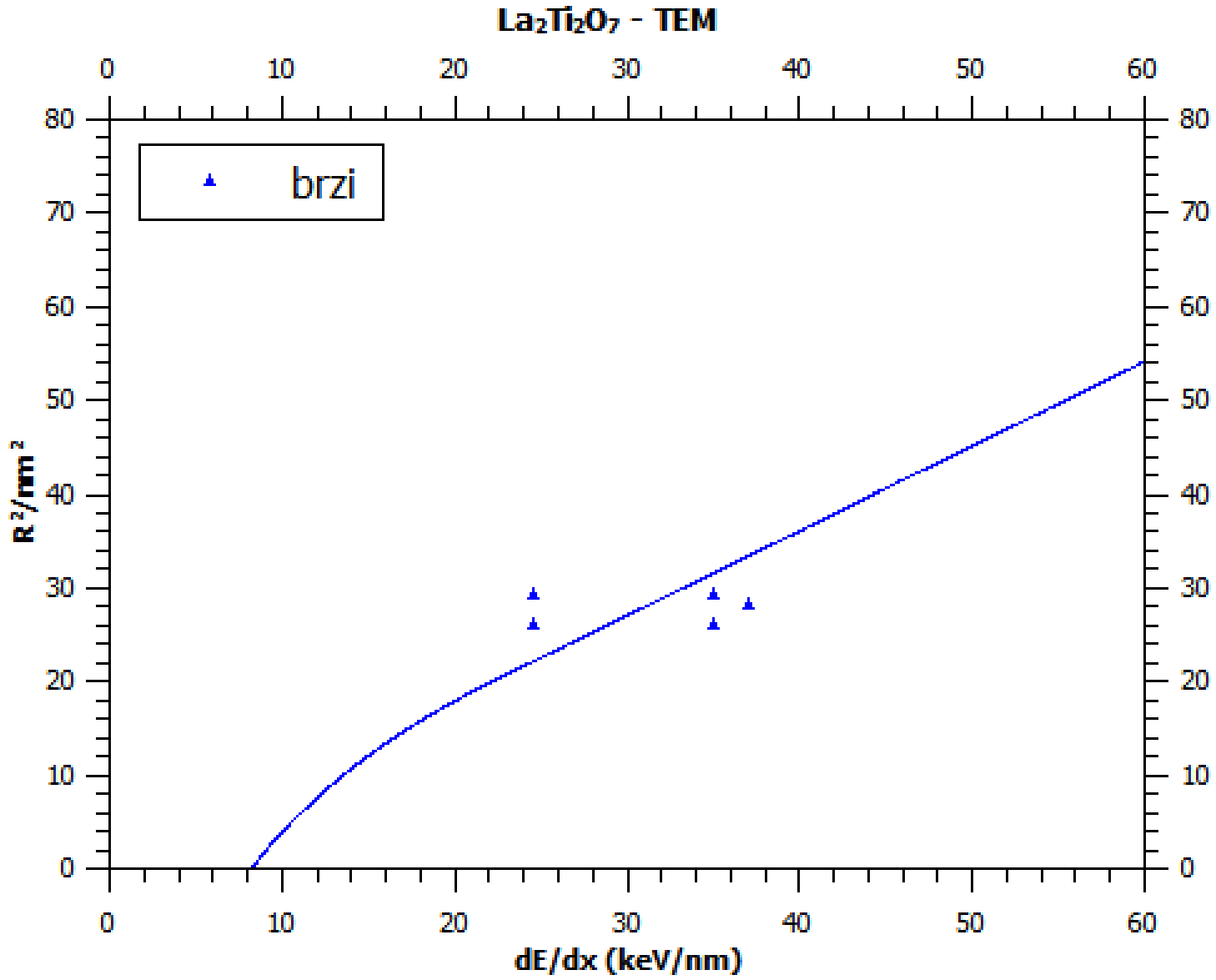
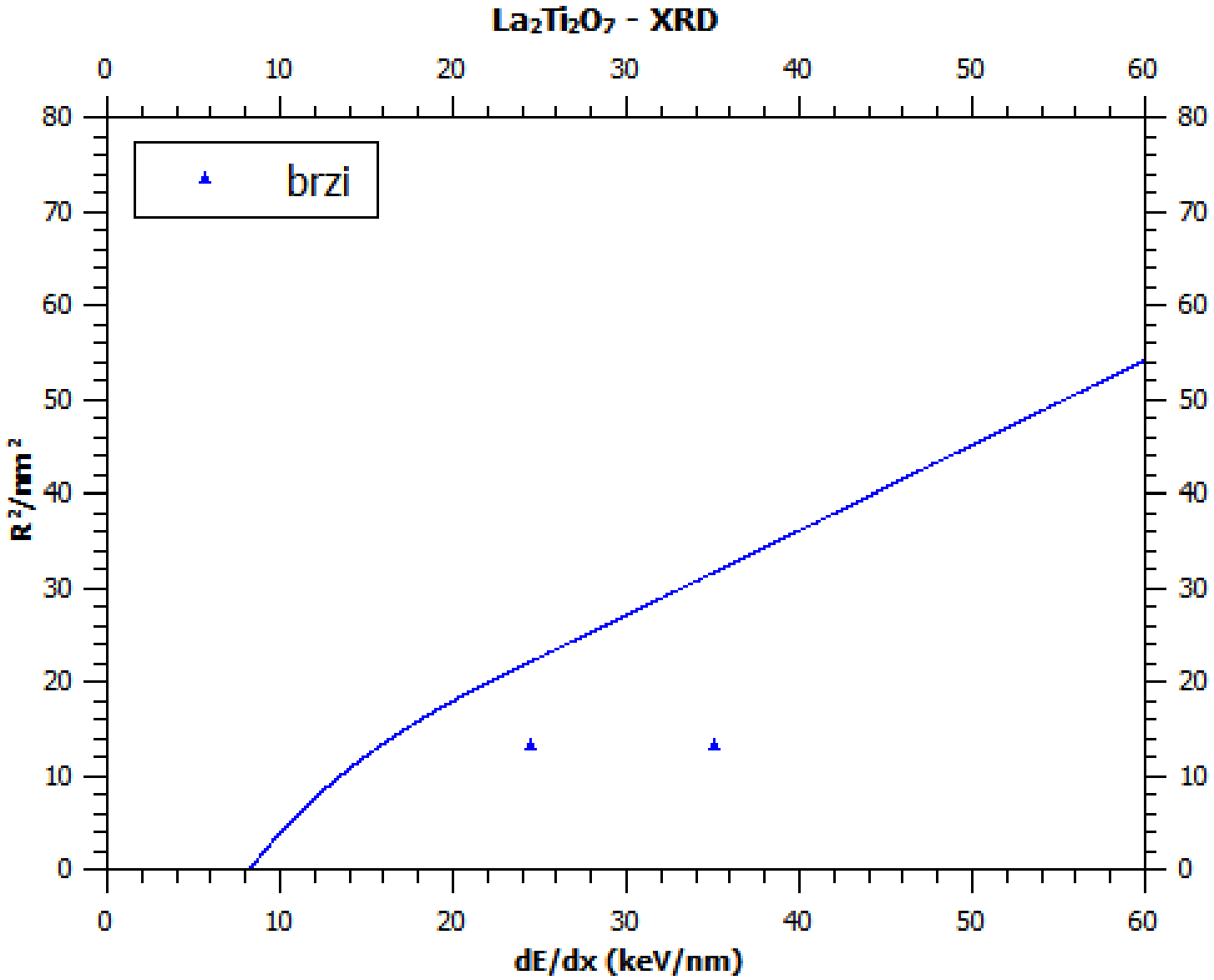
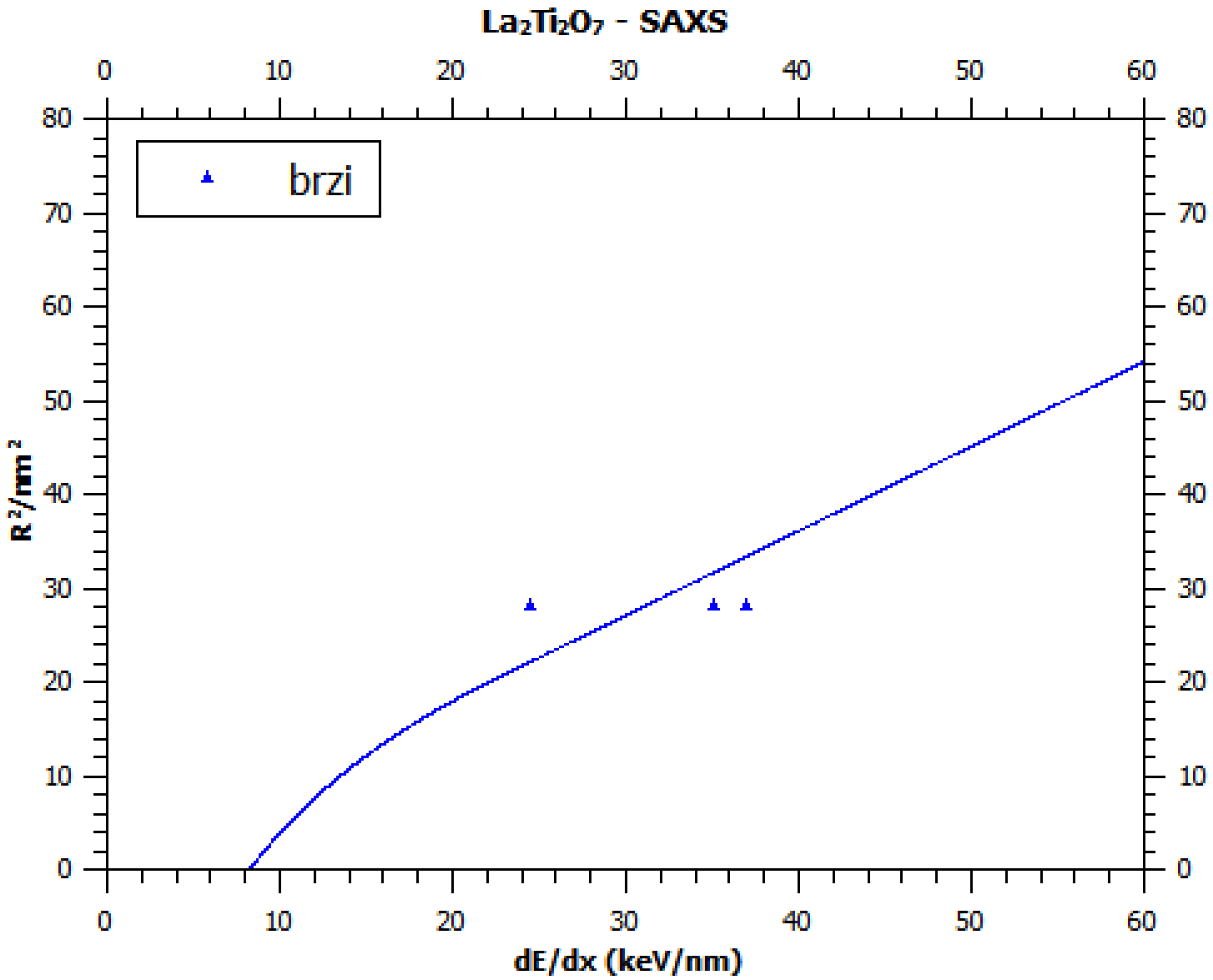
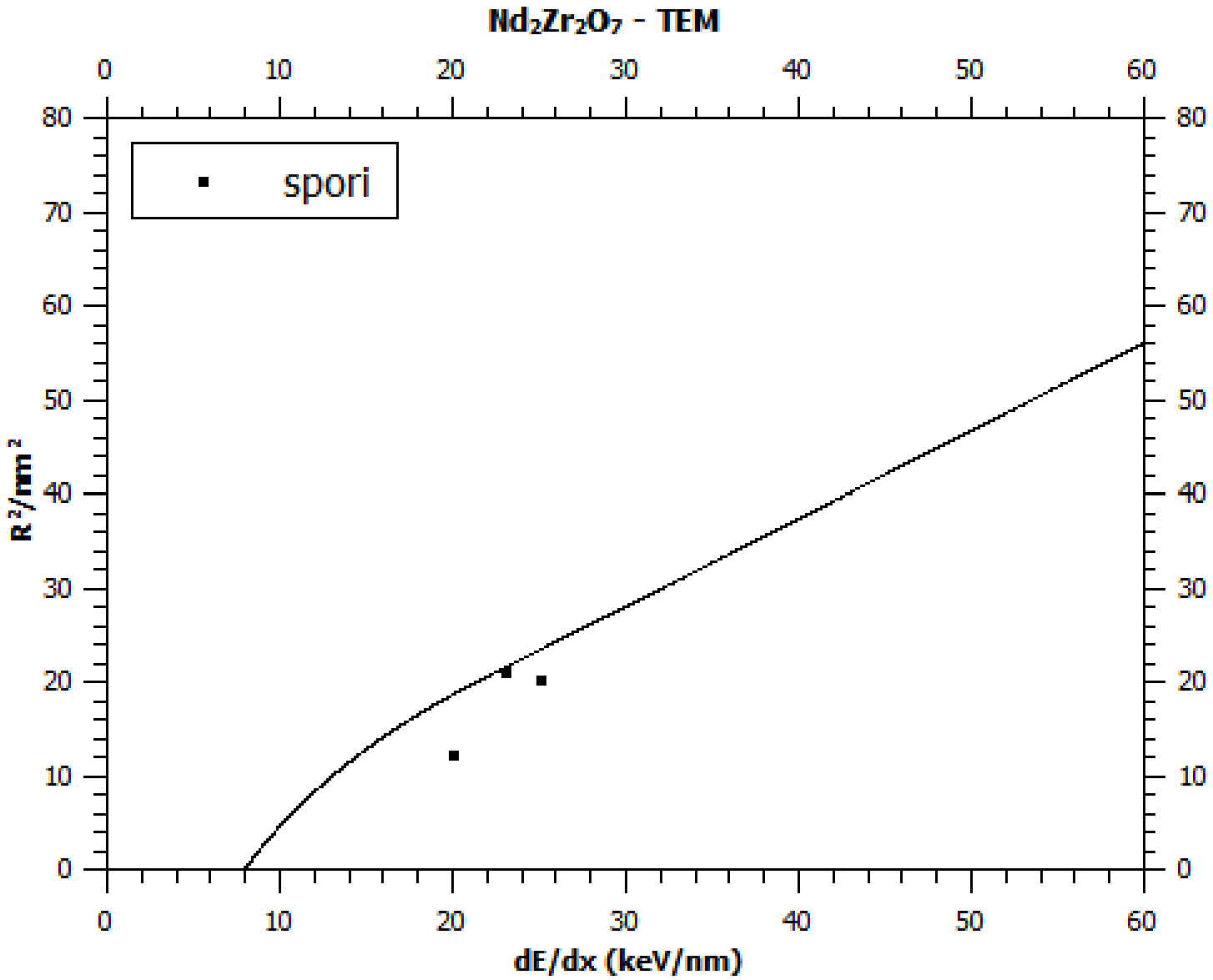
60
70
80

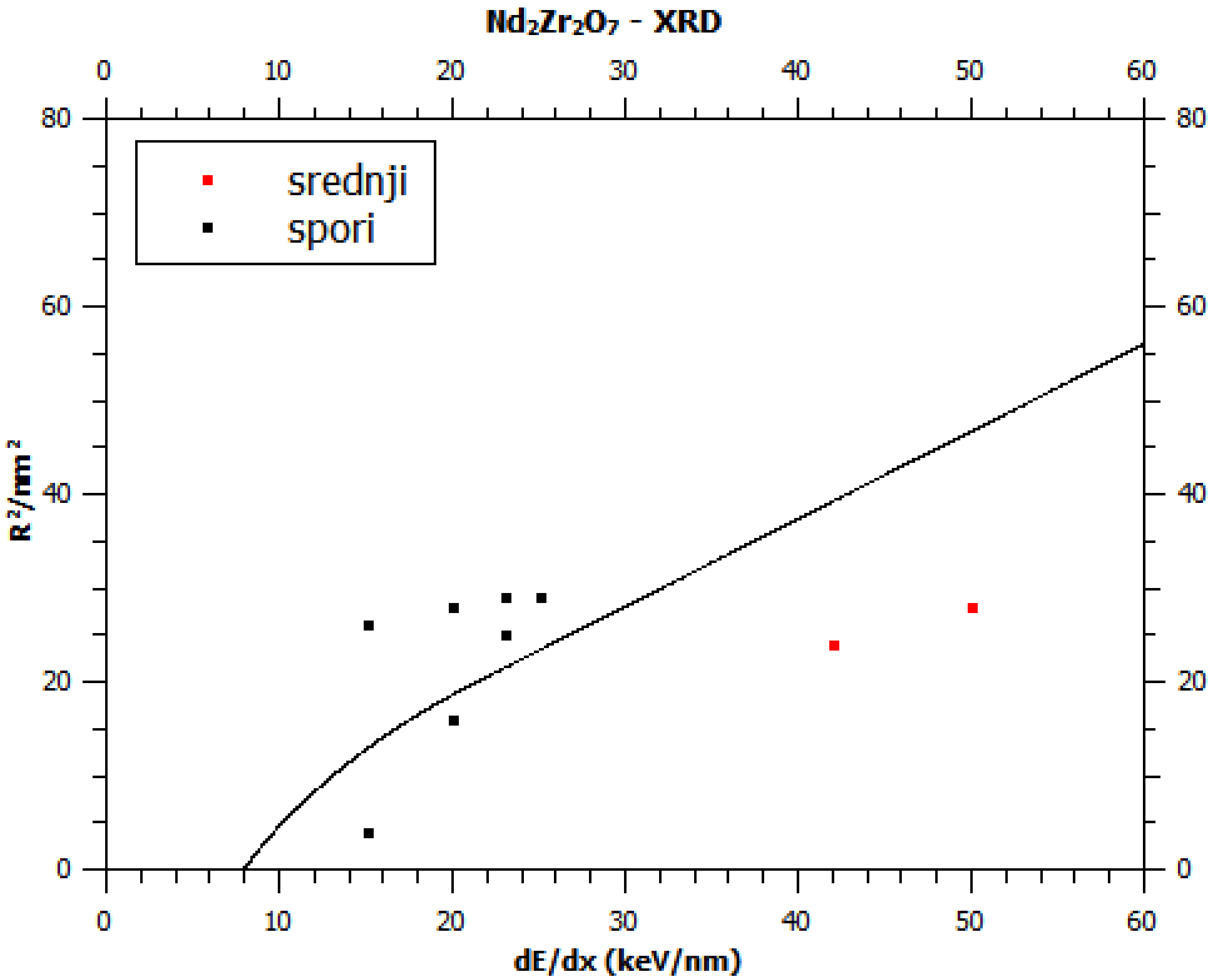

Gd2Zr2O7 - XRD
srednji
brzi
spori
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


La2Ti2O7 - TEM
brzi
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


La2Ti2O7 - XRD
brzi
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


La2Ti2O7 - SAXS
brzi
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


Nd2Zr2O7 - TEM
spori
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
70
80


Nd2Zr2O7 - XRD
srednji
spori
R²/nm²
dE/dx (keV/nm)
0
10
20
30
40
50
60
80