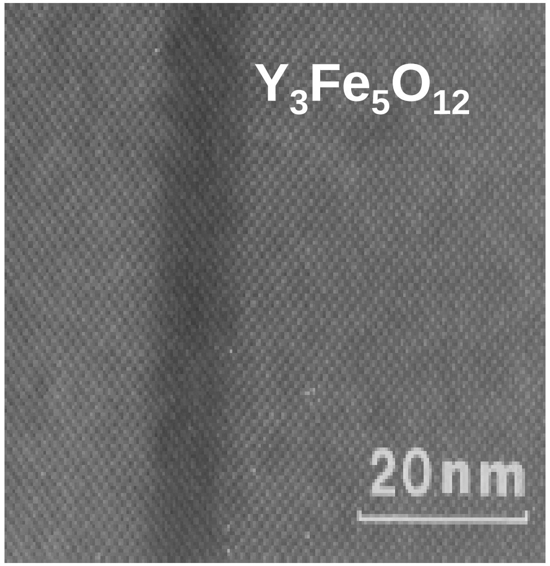
Swift heavy ions and particles tracks in materials

1) Introduction: why radiation effects with swift heavy ions
2) MF/GSI and CIMAP Laboratories
3) Electronic energy deposition by swift heavy ions
4) Material sensitivity
5) Velocity effect and sputtering
6) Inelastic thermal spike model (i-TS model)
    - Metallic materials
    - Insulators
    - Amorphous materials
7) Complex oxides



M. Toulemonde, CIMAP, Caen, France

Radiation Effects

in nuclear materials

Two Damage Sources

Fission fragments: electronic excitation

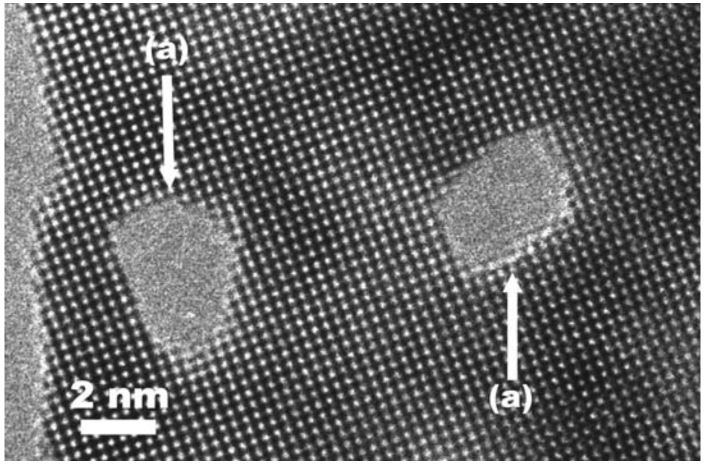
Alpha Decay (nuclear excitation)

In high energy accelerators: electronic excitation

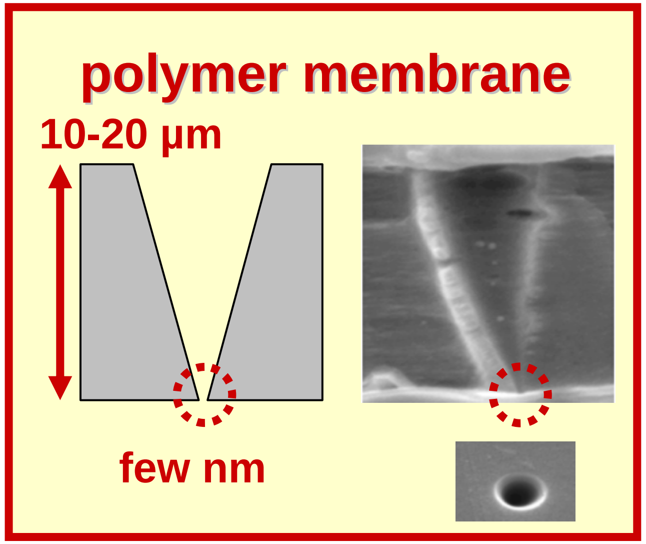
In space: electronic excitation

Basic physics: ~10^{15} Watt/cm^2 (~Petawatt laser) in a nanometer volume

Applications:



Berthelot et al. Phil. Mag. 80(2000)2257



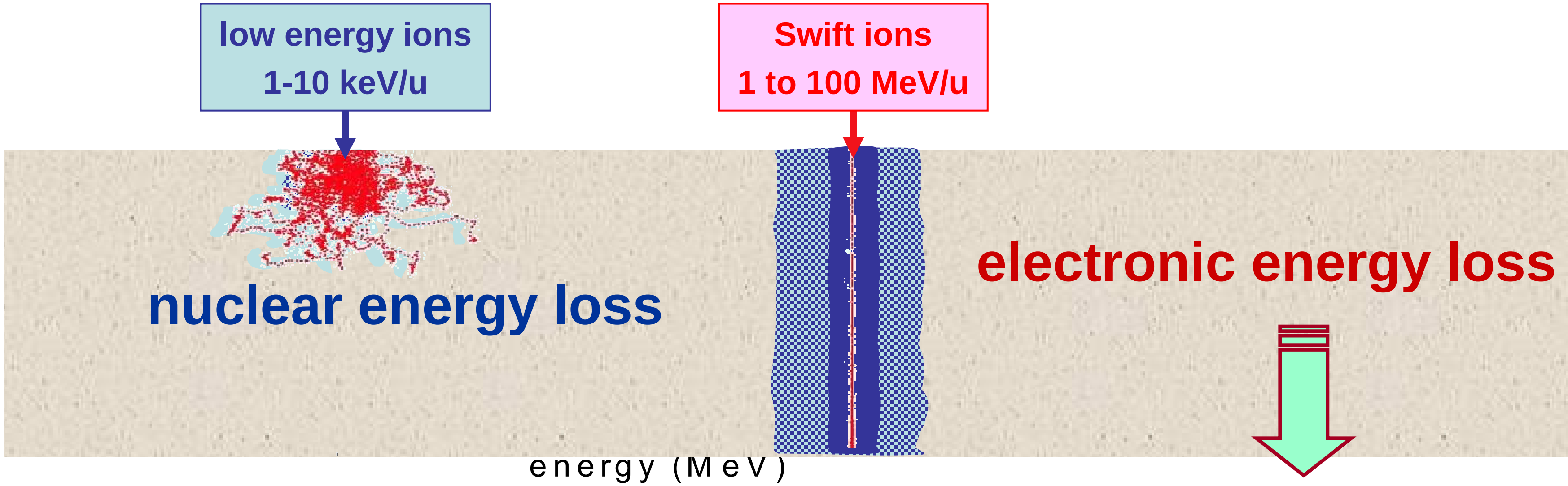
polymer membrane

10-20 µm

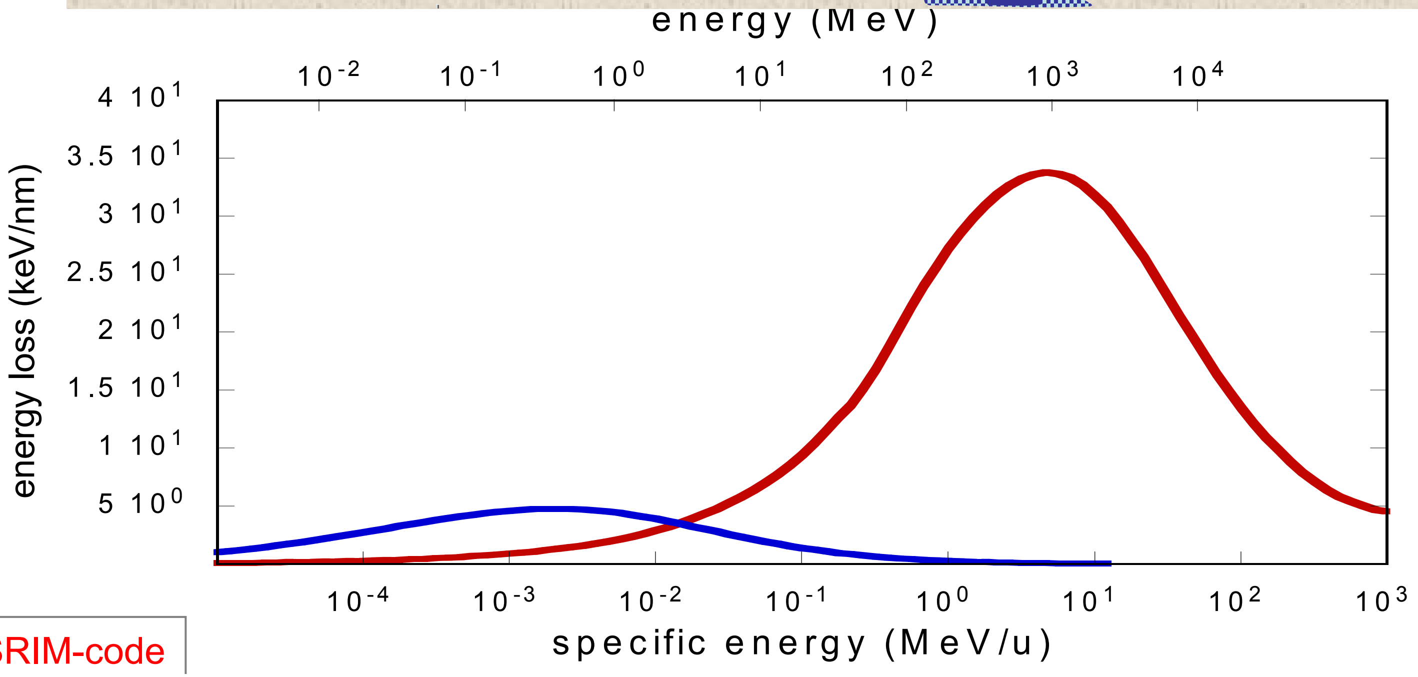
few nm

Z. Siwy et al., Appl. Phys. A 76 (2003) 781

Scheme of energy deposition of an ion in mattter

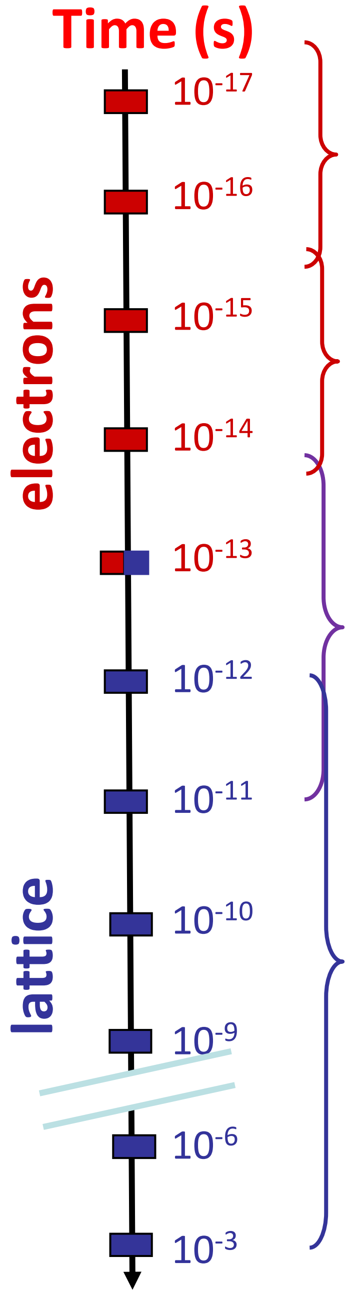


energy
> 0.1 MeV/u



SRIM-code

Attosecond deposition in nm scale
~10^{22}W/cm^3

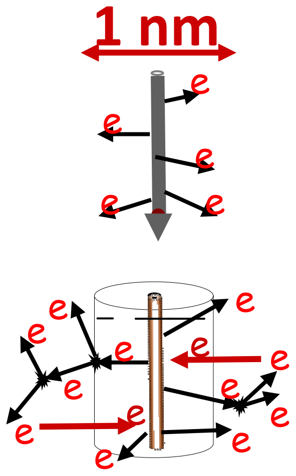


Stage 1: Energy deposition on electrons (e)

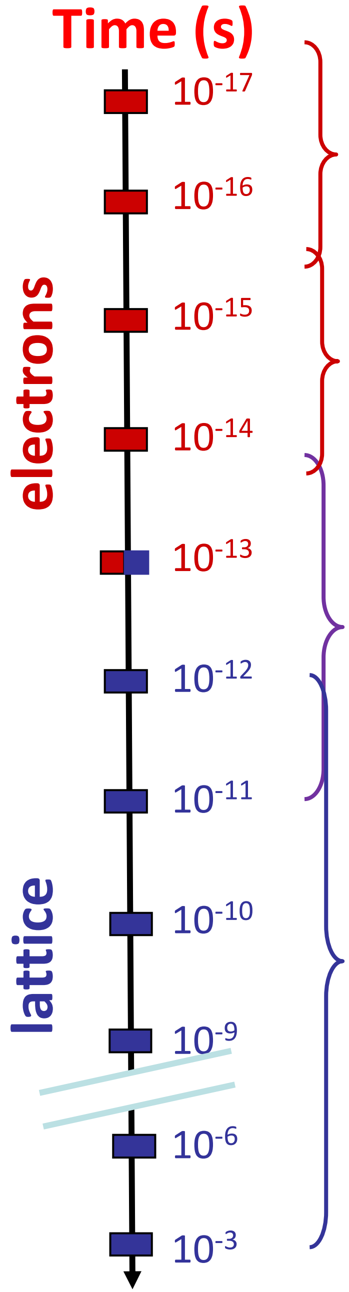
- generation of primary-electrons
- ionization
- creation of a Coulomb field

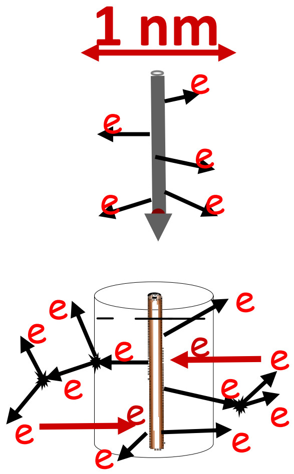
Stage 2: Plasma formation

- electrons cascades
- screening of Coulomb field
- thermalization of electron temperature



Attosecond deposition in nm scale ~10^{22}W/cm^3





Stage 1: Energy deposition on electrons (e)

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- electrons cascades
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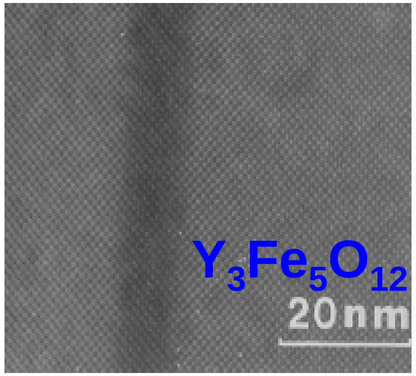
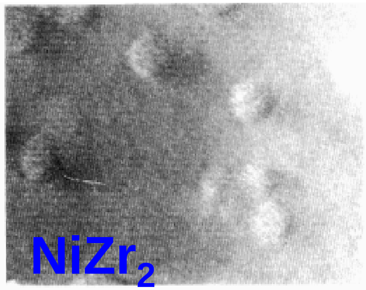
Toulemonde and Studer
Phil. Mag. A58(1988)799

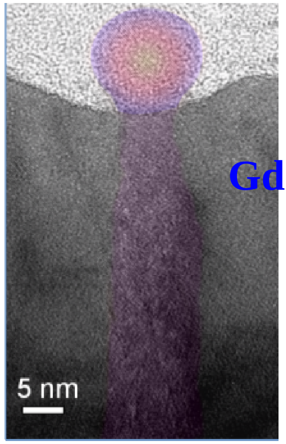


Barbu et al. Europhys.
Lett. 15(1991)3713



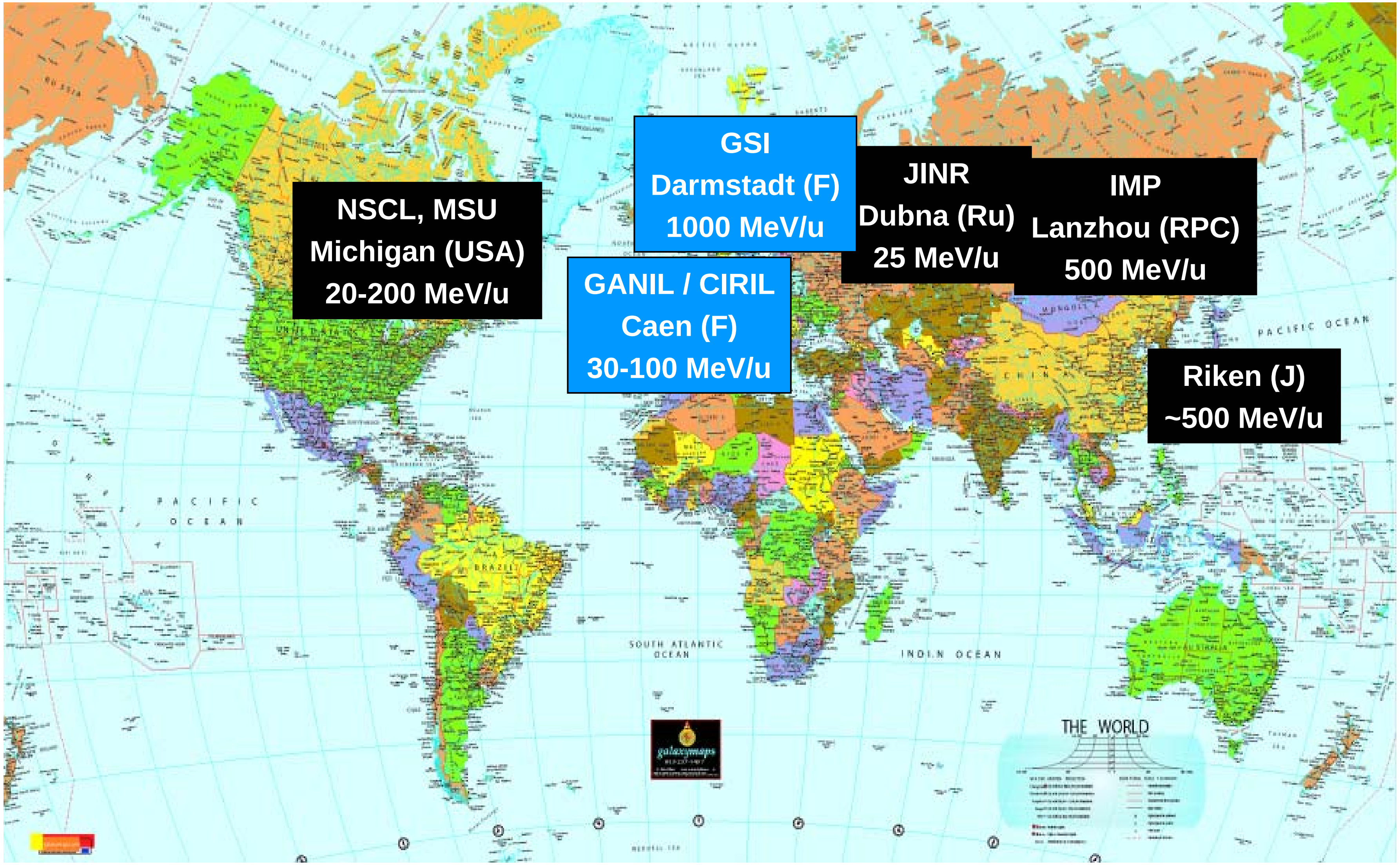
Ces photos sont extraites d'un article soumis à Europhysics Letters par A. BARBU, A. DUNLOP, D. LESUEUR, CEA/CEREM/Laboratoire des Solides Irradiés, Ecole Polytechnique et R.S. AVERBACK, Dept. of Materials Science and Engg URBANA, USA.

Jiamin Zhang et al.
AP105(2009)113510



$Gd_2Zr_2O_7$

Large accelerator facilities with materials research activities



NSCL, MSU
Michigan (USA)
20-200 MeV/u

GSI
Darmstadt (F)
1000 MeV/u

GANIL / CIRIL
Caen (F)
30-100 MeV/u

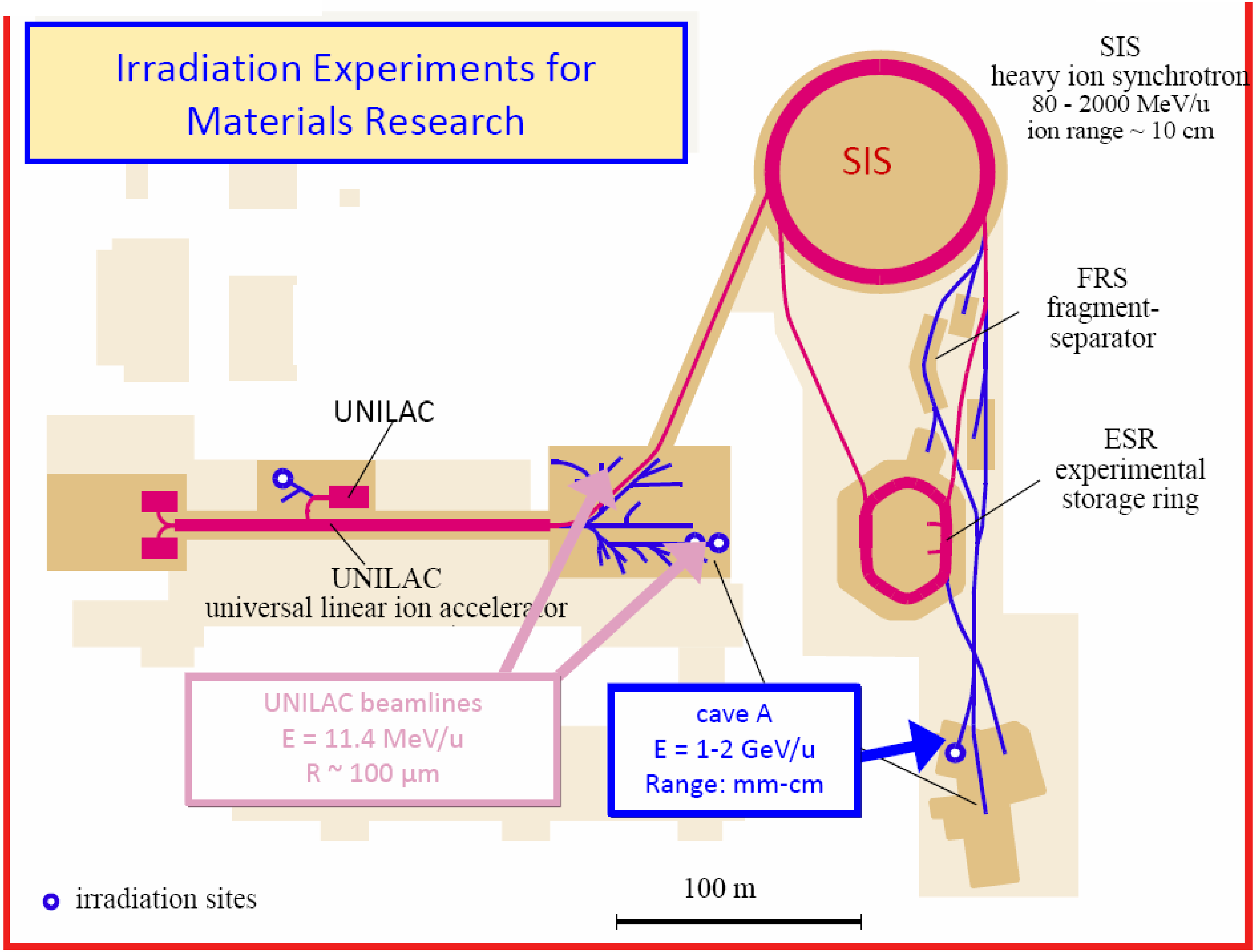
JINR
Dubna (Ru)
25 MeV/u

IMP
Lanzhou (RPC)
500 MeV/u

Riken (J)
~500 MeV/u

GSI- Darmstadt

Irradiation Experiments for Materials Research



UNILAC beamlines
E = 11.4 MeV/u
R ~ 100 µm

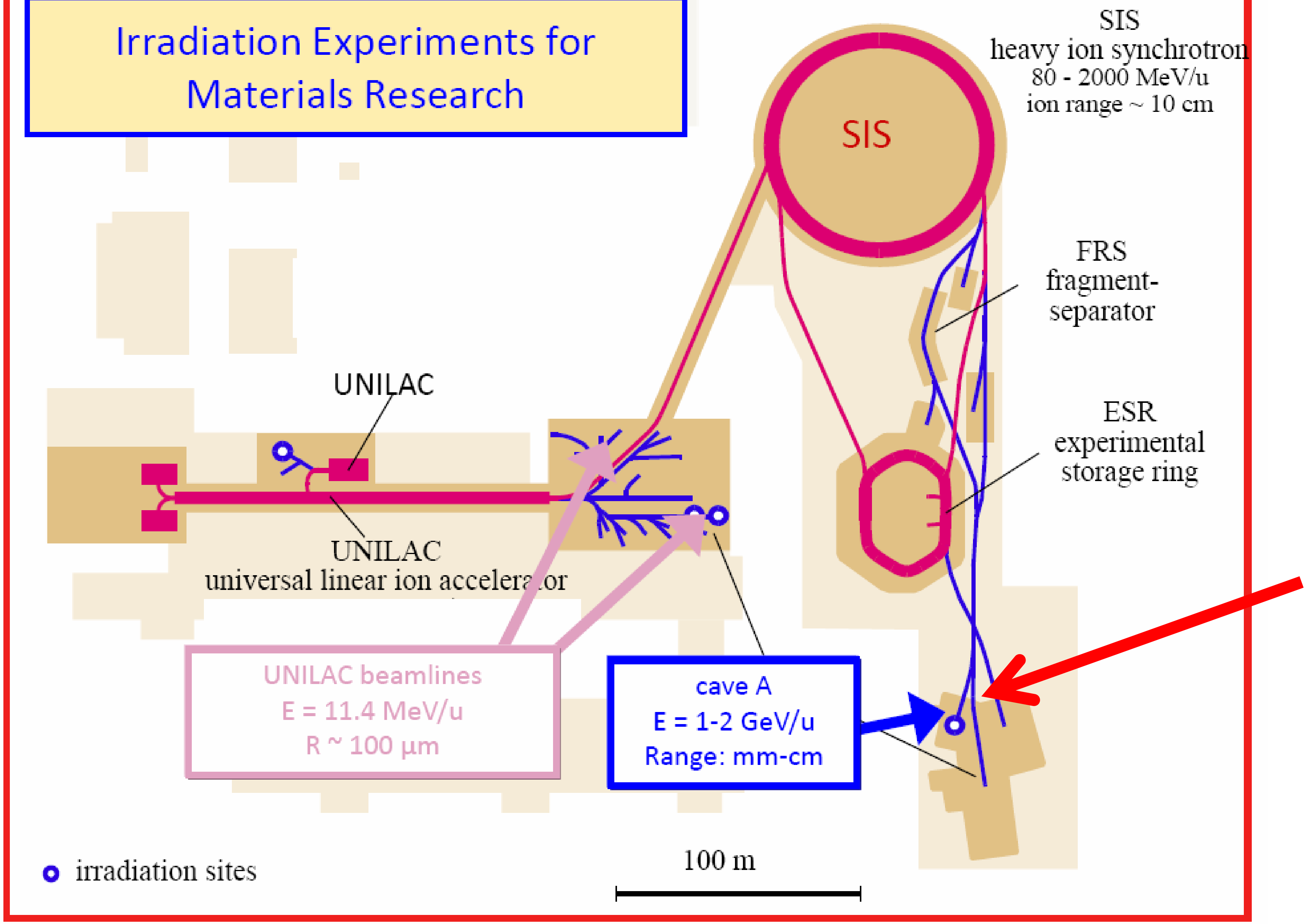
cave A
E = 1-2 GeV/u
Range: mm-cm

● irradiation sites

GSI- Darmstadt

Darmstadt-February-2011
Courtesy C. Trautmann

Irradiation Experiments for Materials Research



SIS
heavy ion synchrotron
80 - 2000 MeV/u
ion range ~ 10 cm

FRS
fragment-
separator

ESR
experimental
storage ring

UNILAC

UNILAC
universal linear ion accelerator

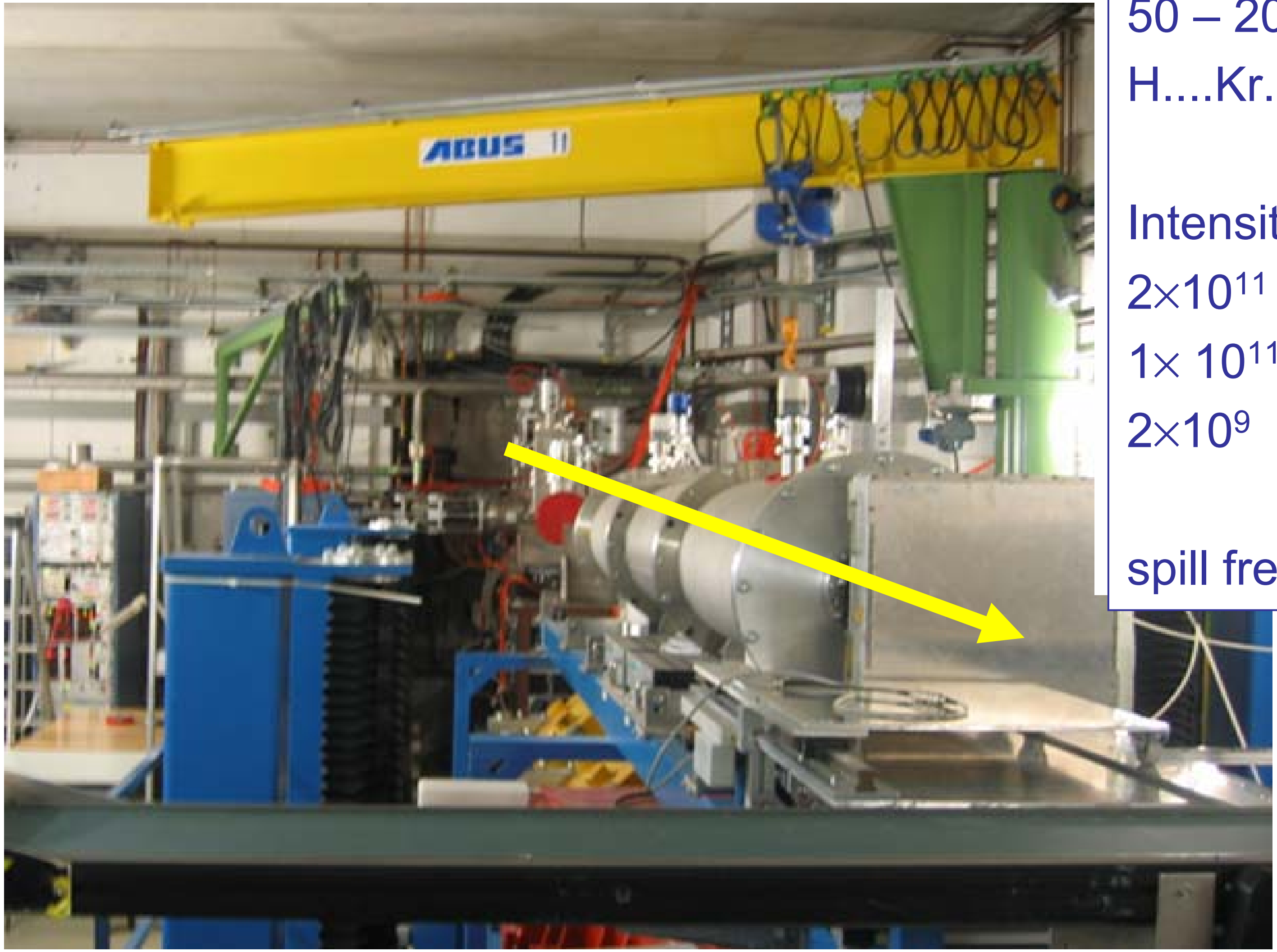
UNILAC beamlines
E = 11.4 MeV/u
R ~ 100 µm

cave A
E = 1-2 GeV/u
Range: mm-cm

○ irradiation sites

100 m

Cave A @ Synchrotron SIS



50 – 2000 MeV/u

H....Kr...Xe....U

Intensities

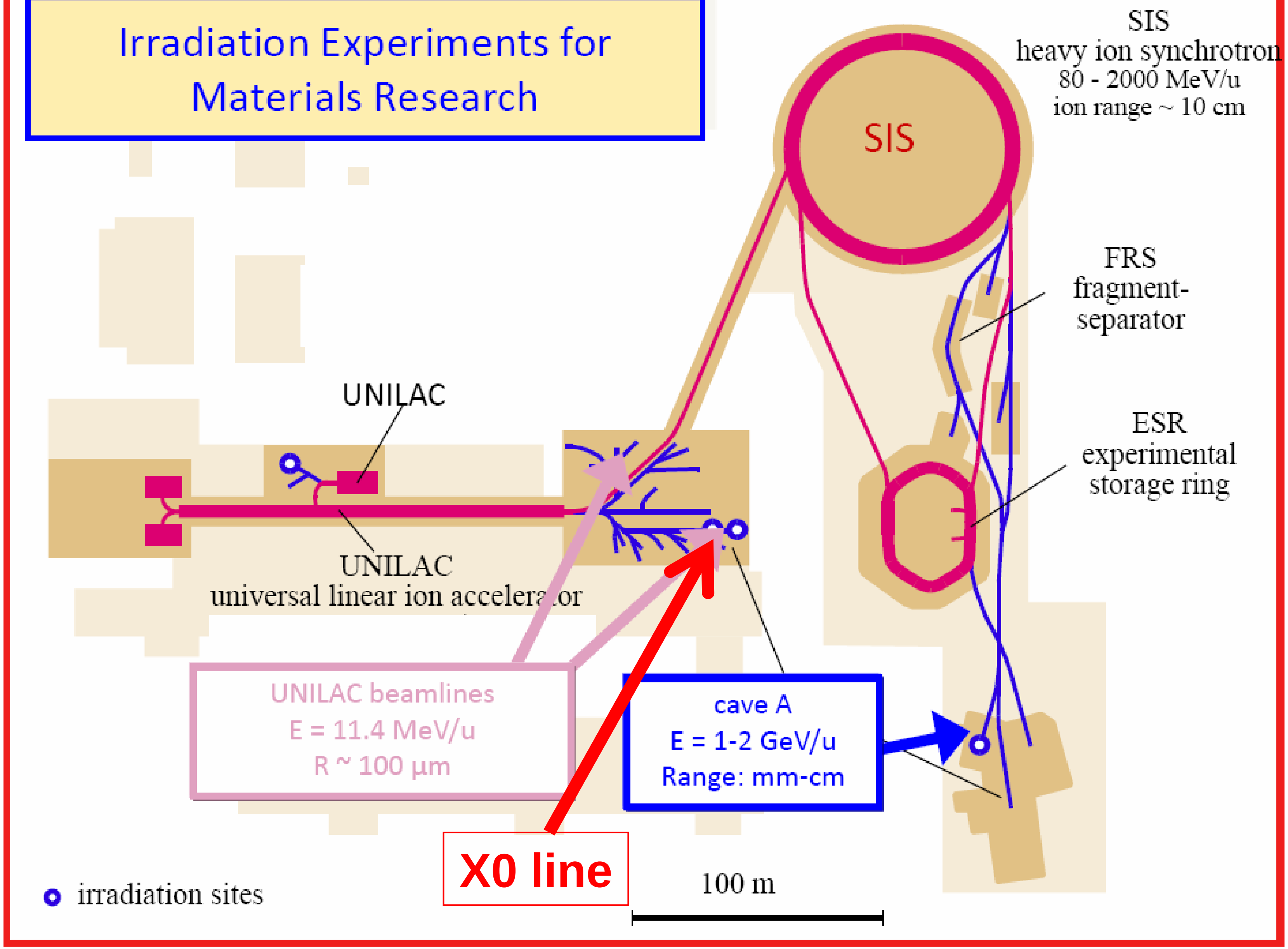
2×10^{11}	Ne / spill
1×10^{11}	Ar / spill
2×10^{9}	U / spill

spill frequency < 1 Hz

cave shared by Biophysics, Atomphysics, and Materials Research

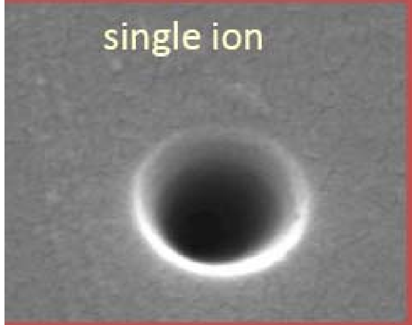
GSI- Darmstadt

Irradiation Experiments for Materials Research



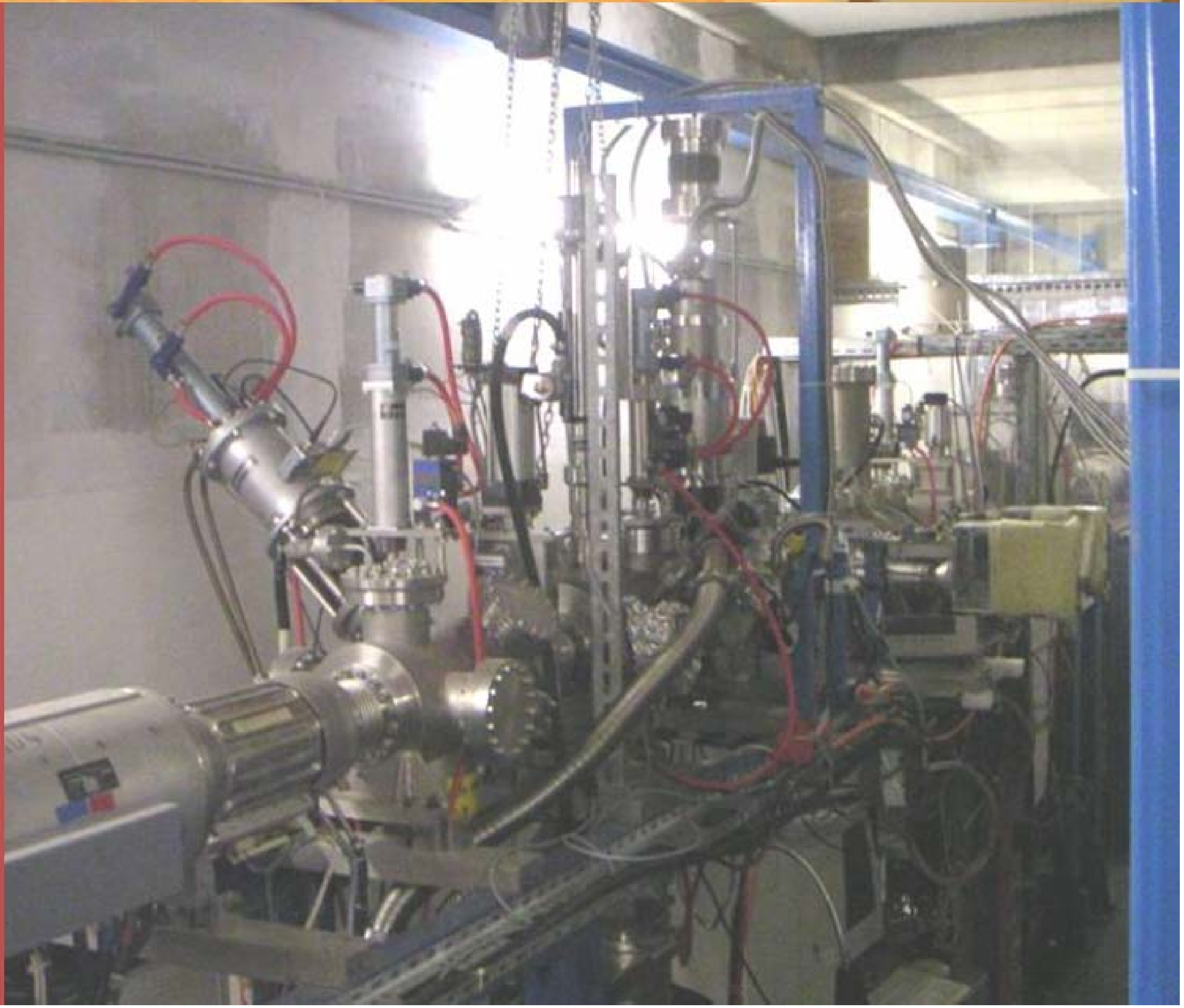
Beamline X0 (UNILAC)


random


single ion

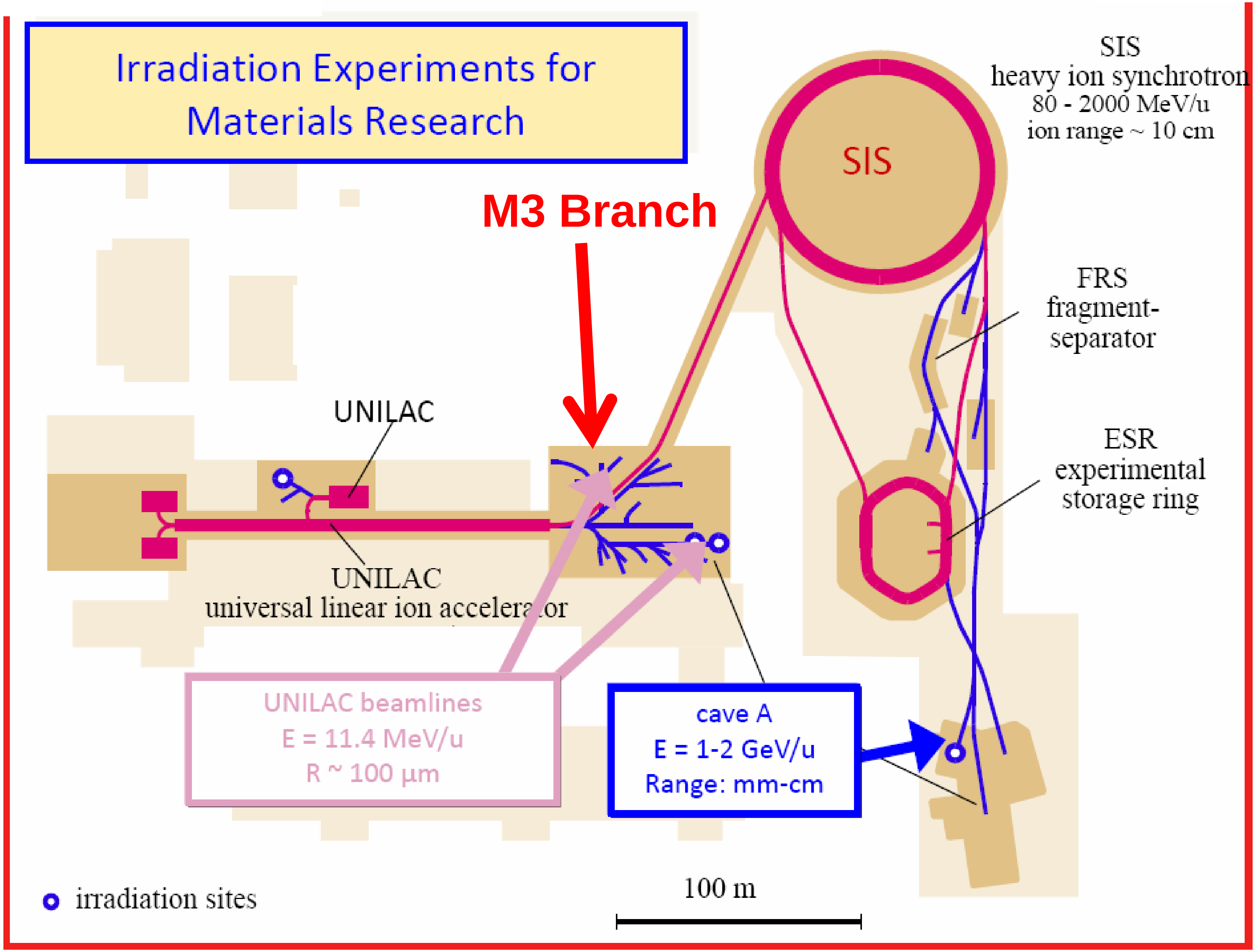

ordered

microprobe



GSI- Darmstadt

Irradiation Experiments for Materials Research

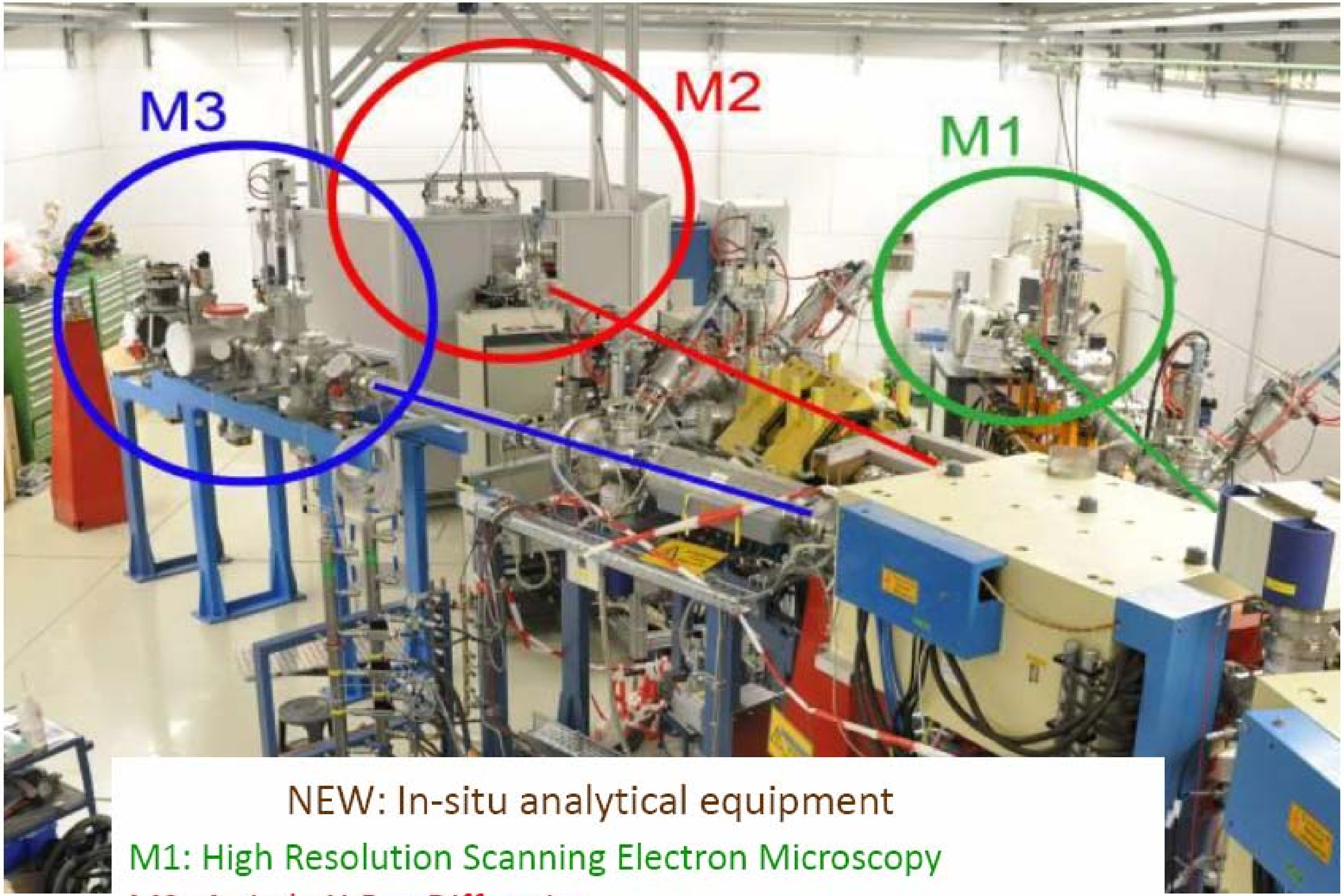


UNILAC beamlines
E = 11.4 MeV/u
R ~ 100 µm

cave A
E = 1-2 GeV/u
Range: mm-cm

Courtesy C. Trautmann

M- Branch



NEW: In-situ analytical equipment

M1: High Resolution Scanning Electron Microscopy

M2: 4-circle X-Ray Diffraction

M3: Spectroscopy (IR, UV/Vis, luminescence, RGA, …)

CIMAP

Centre de recherche sur les Ions, les MAtériaux et la Photonique

http://www.cimap.ensicaen.fr/

Photonics

Ion-matter interaction

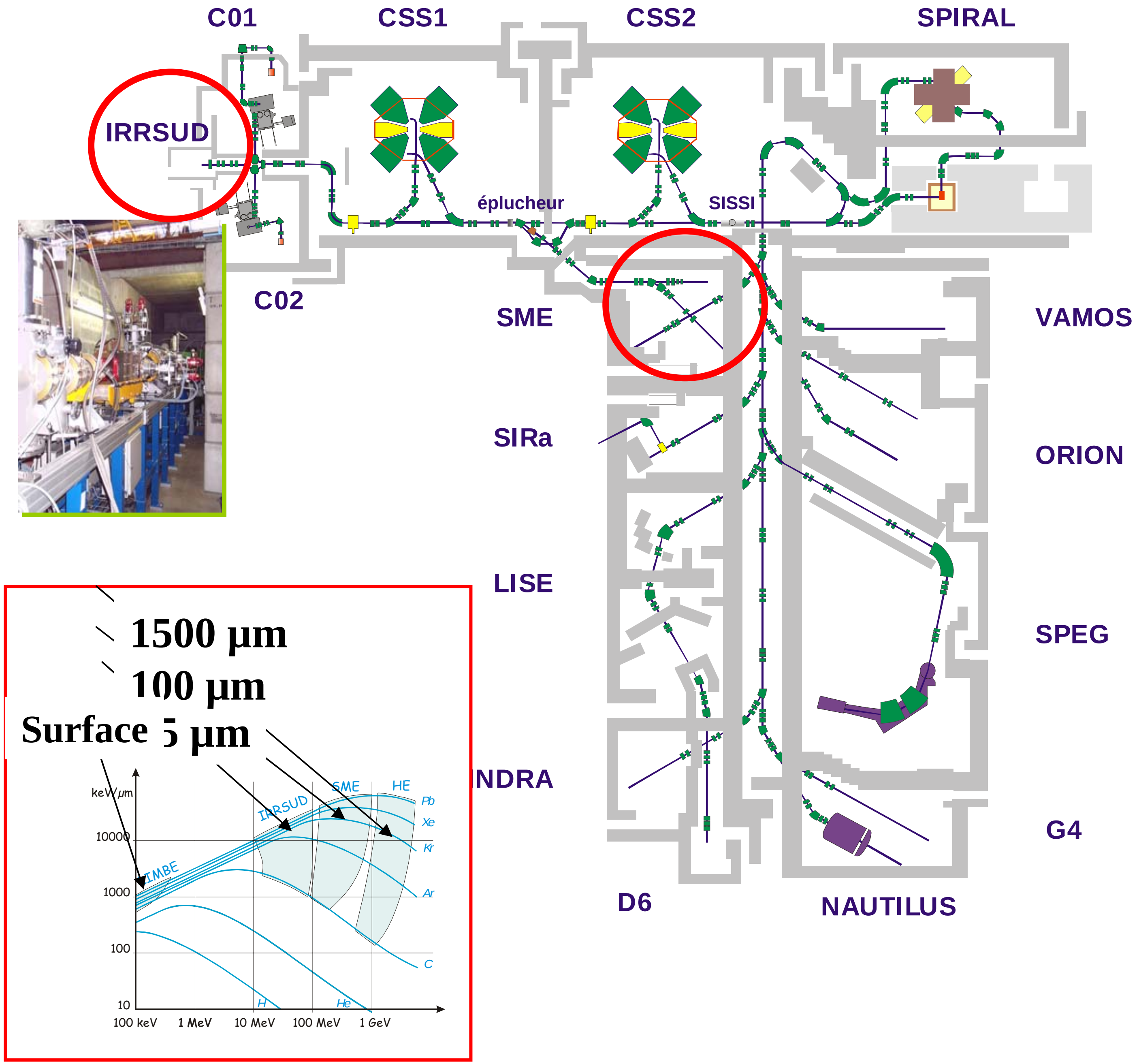
Ciril
GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

Welcome for GANIL

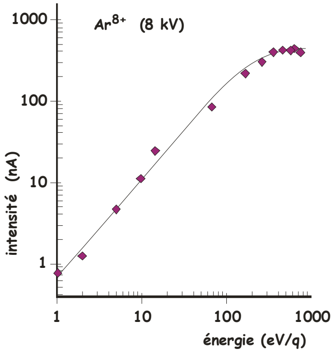
Number of researchers

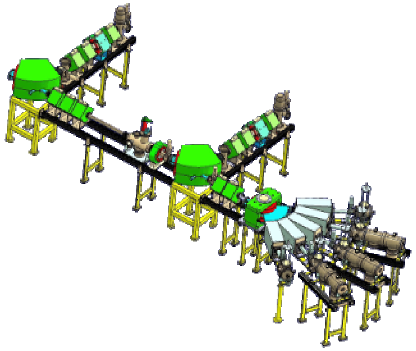
10 material irradiation	15 atomic physics
5 theory (DTDFT)	23 photonics and material science

Darmstadt-February-2011

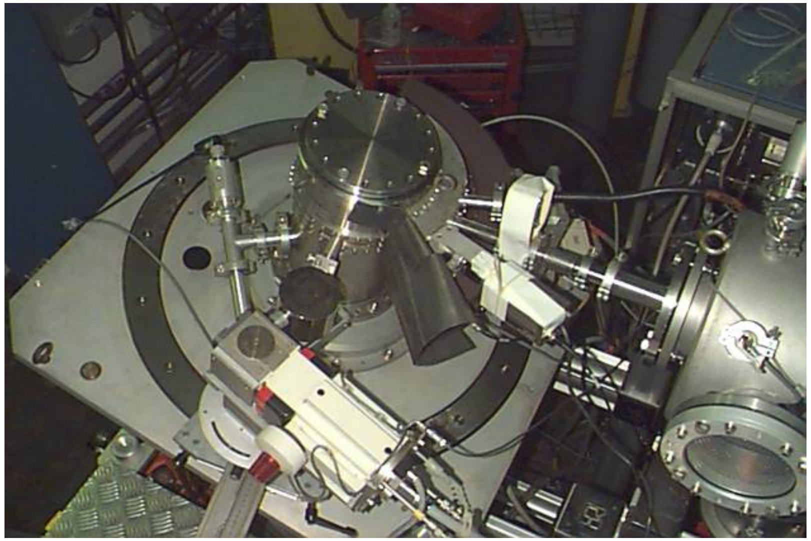


ARIBE
ITSLEIF





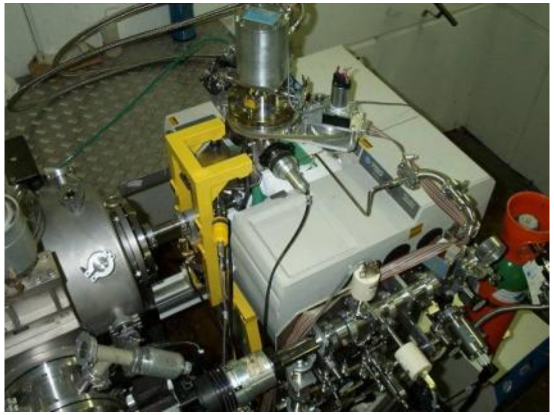
On-line structural material modifications:



On-line WAXS
CIRIL

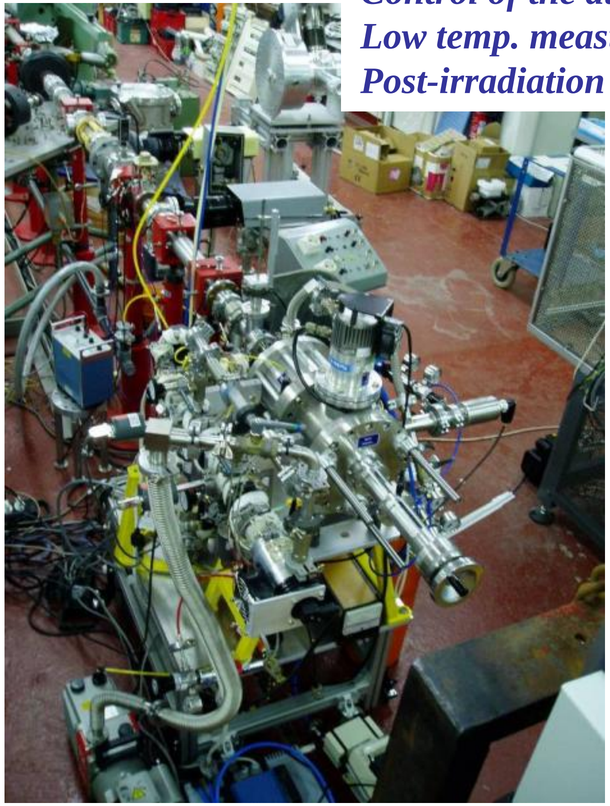
On-line AFM
Duisburg-Essen / CIRIL

On-line measurements of chemical modification



CASIMIR *Irradiation in-situ FTIR measurements at 8 K*

Control of the atmosphere
Low temp. measurements
Post-irradiation effects

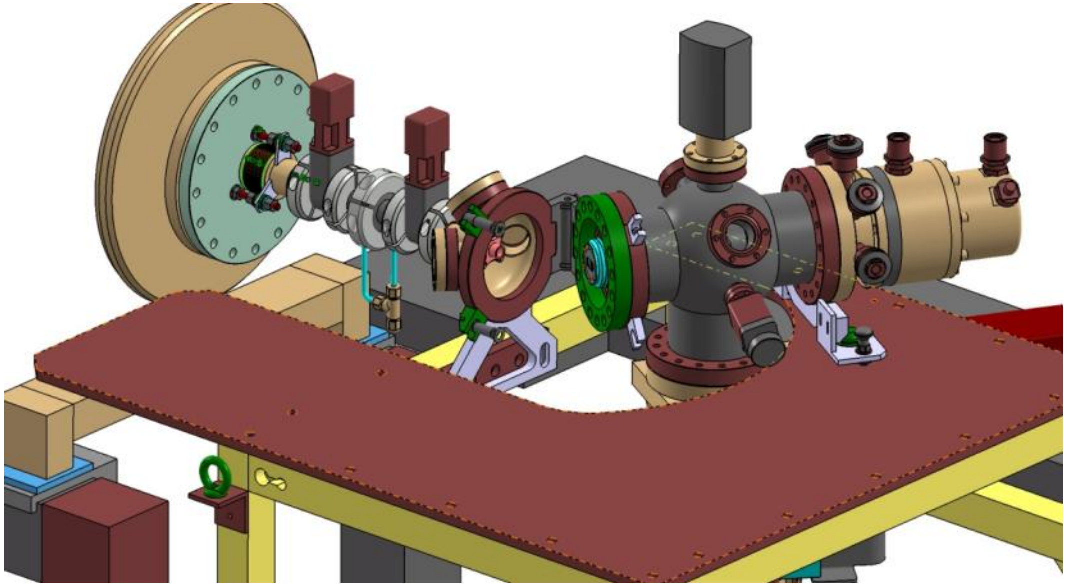


Radioxidation
Oxygen consumtion

On-line FTIR
films et gas

SPORT:
Spectroscopie Optique Résolue dans le temps

On line on
IRRSUD (≈0.5 - 1 MeV/A C to U)
SME (≈5 - 13 MeV/A C to U)



Chamber:
Cryo cooler 10 K – RT
Good vacuum 10^{-8} 10^{-9} mbar

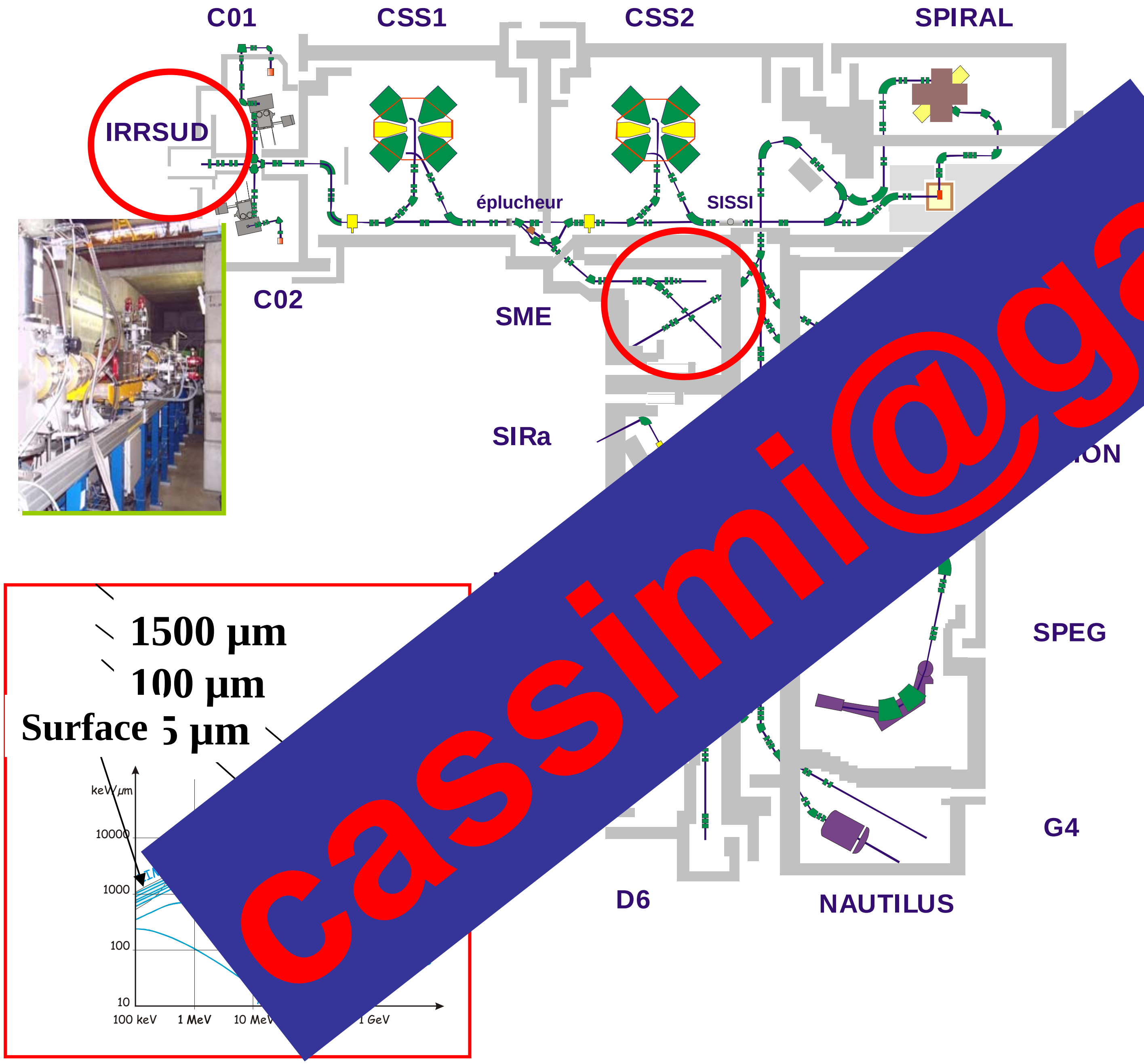
Spectrogaphs
Two CP 140 in parallel
Horiba Jobin Yvon
« low resolution » 17 nm/channel
Simultaneous full range
190 -780 nm

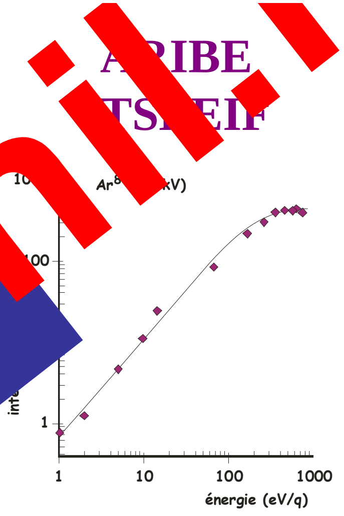
Timing
200 ps – ms
Single ion single photon for ns-µs range
Bunch mode possible for µs-ms mode

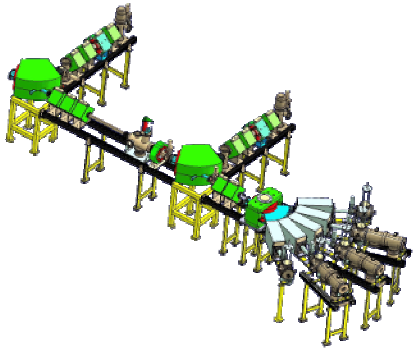
First tests June 2011

Electronics
32 channels
Fast amplifiers
CFD
TDC multi stops

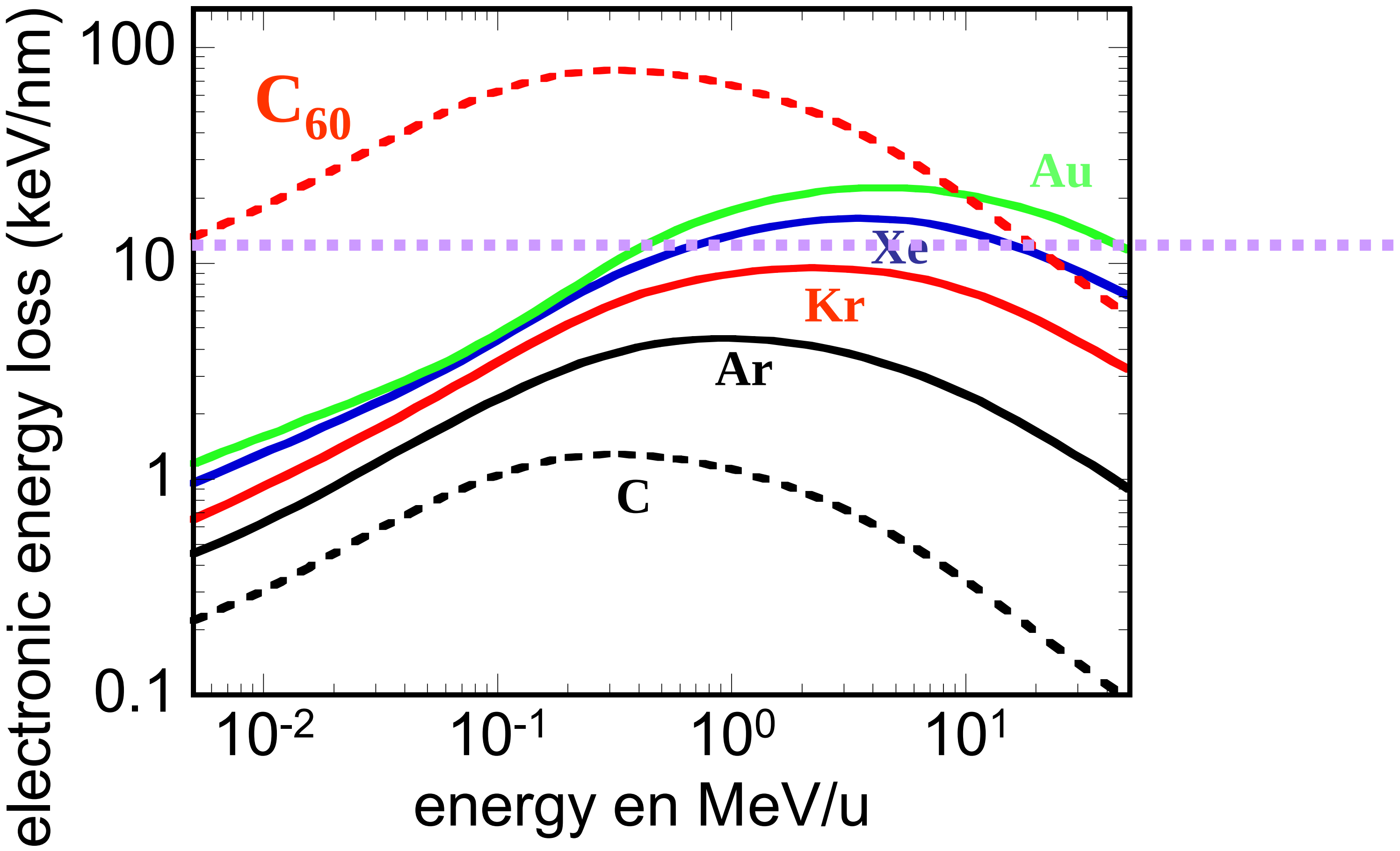
Detectors
Two, 16 channels
Hamamatsu PM


C01
CSS1
CSS2
SPIRAL
IRRSUD
éplucheur
SISSI
C02
SME
SIRa
ON
SPEG
G4
D6
NAUTILUS
1500 µm
100 µm
Surface 5 µm
keV/µm
10000
1000
100
10
100 keV
1 MeV
10 MeV
1 GeV


IBE
TS
EIF
Ar8
kV)
10
100
1
1
10
100
1000
énergie (eV/q)



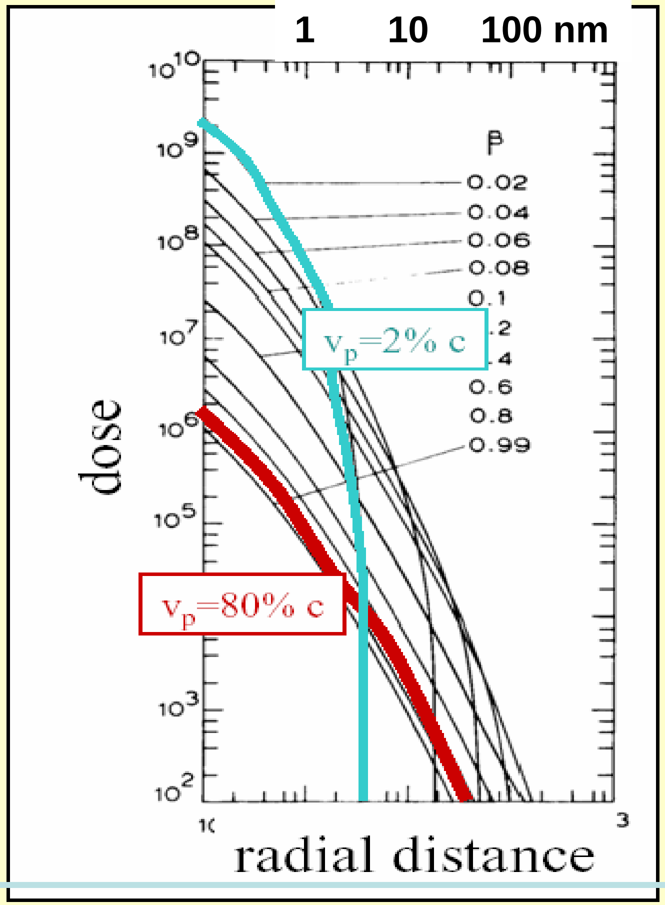
Energy deposition



SRIM and TRIM95 J. P. Biersack et al. Nucl. Instr. Meth. 174 (1980) 257

Energy generation on electrons

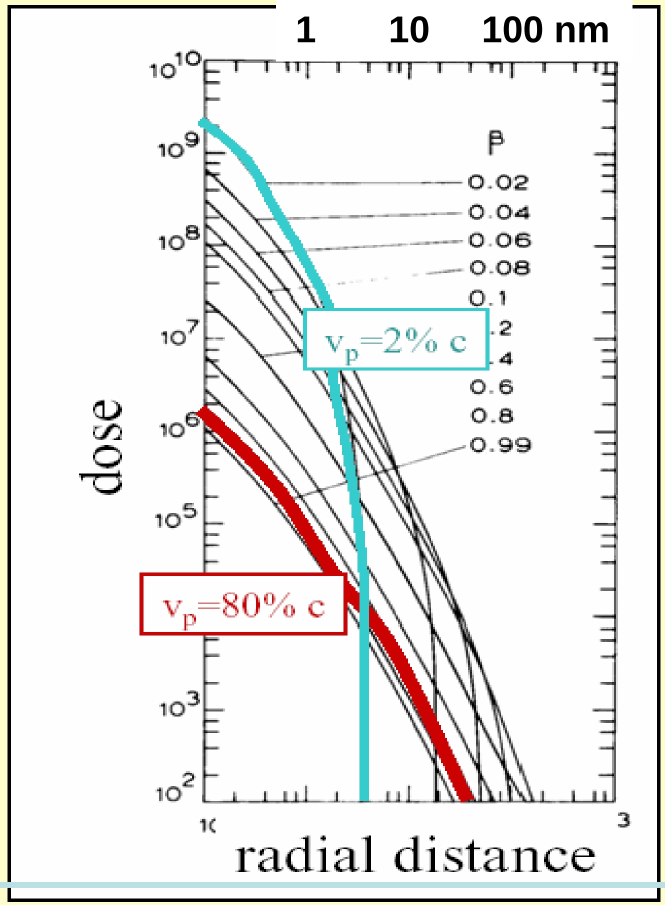
Waligorski et al. Nucl. Tracks Rad. Meas. 11(1986)309, B. Gervais PhD Thésis(1994), Caen



Kobetich et al. Phys Rev.170(1968)391 **$\sim 1/r^2$**

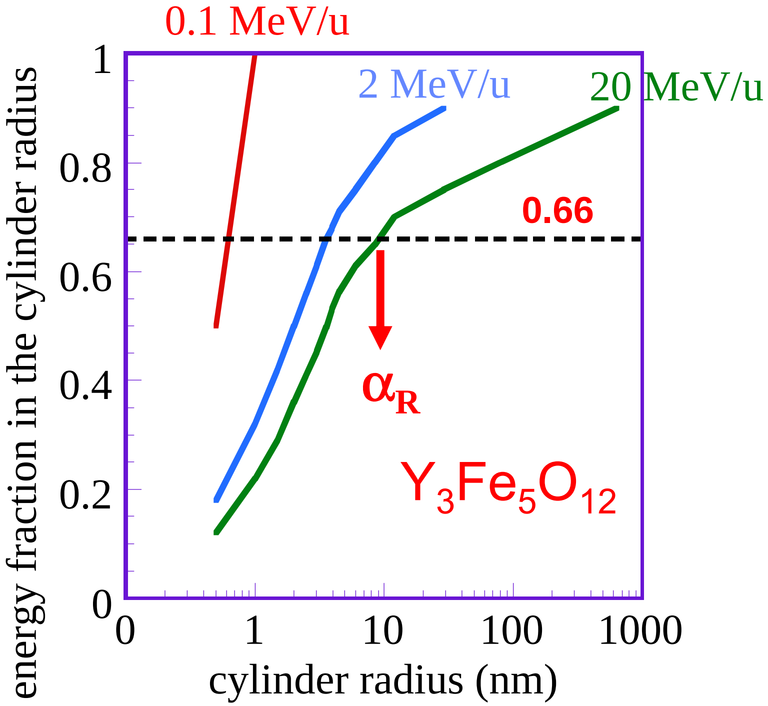
Energy generation on electrons

Waligorski et al. Nucl. Tracks Rad. Meas. 11(1986)309



Kobetich et al. Phys Rev.170(1968)391 ~$1/r^2$

Mean absorption radius α_R

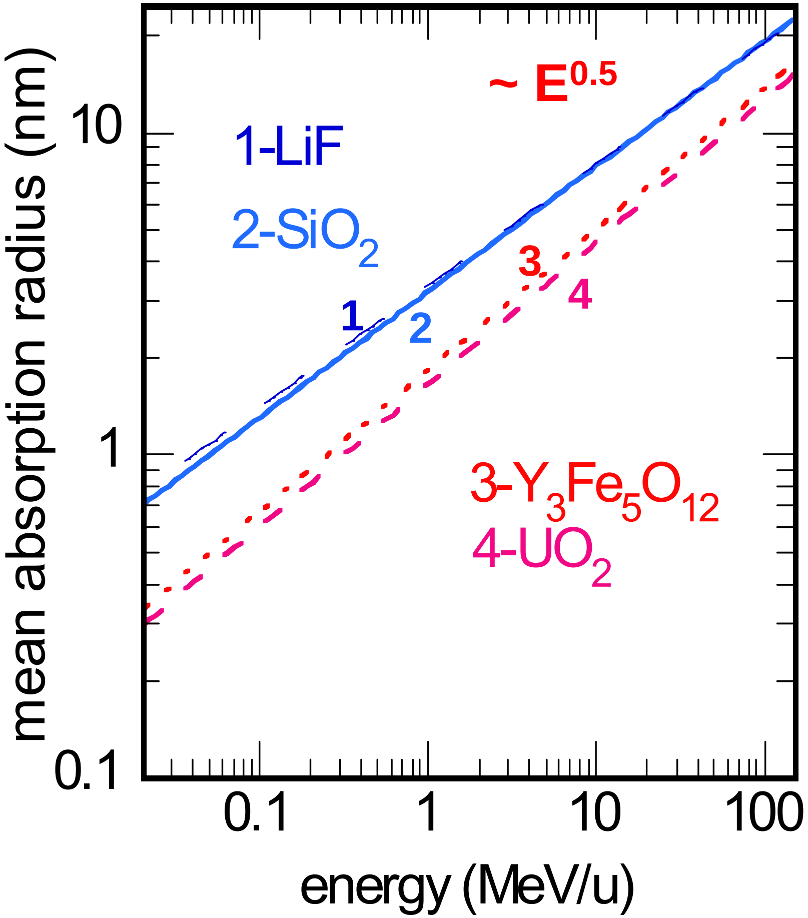


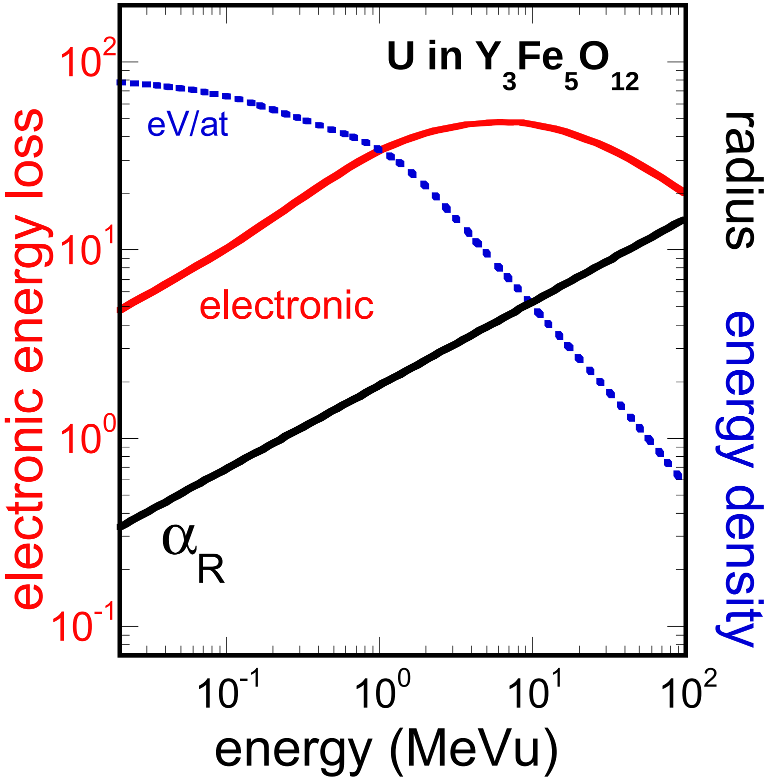
$R<\alpha_R$	$R>\alpha_R$
10-100 eV/at	0.01-0.1eV/at

Energy generation on electrons

Waligorski et al. Nucl. Tracks Rad. Meas. 11(1986)309

Mean absorption radius α_R in different materials



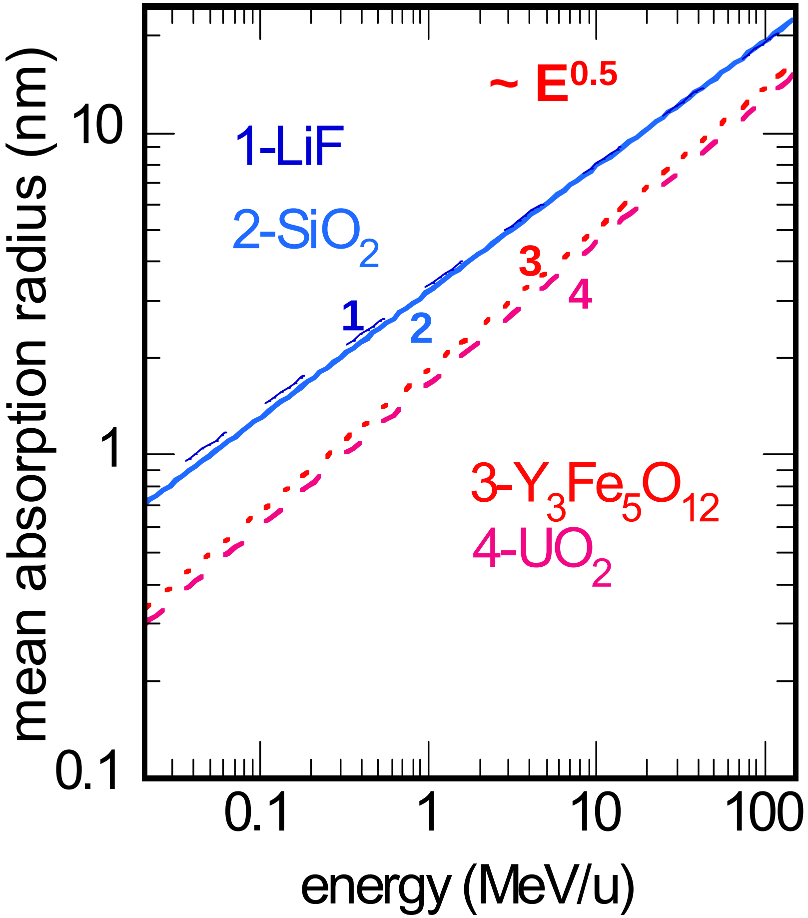


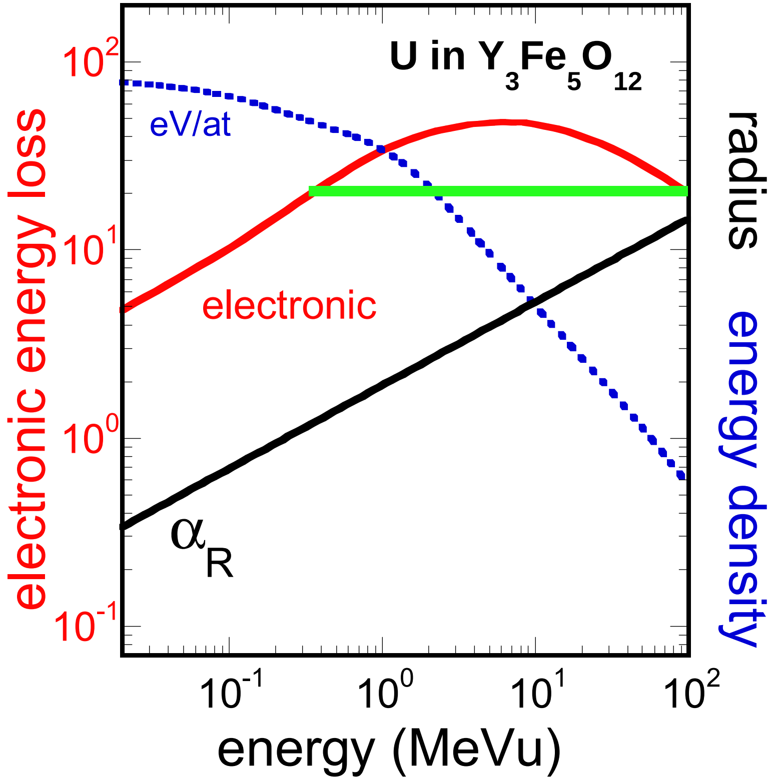
Toulemonde et al. Mat-Fys-Medd-52(2006)263

Energy generation on electrons

Waligorski et al. Nucl. Tracks Rad. Meas. 11(1986)309

Mean absorption radius α_R in different materials





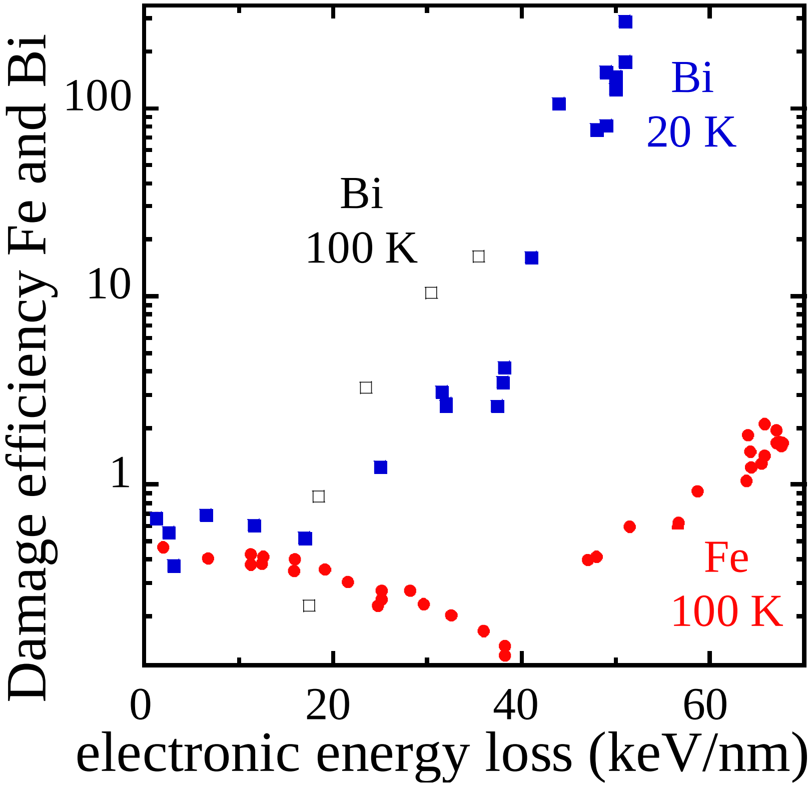
Toulemonde et al. Mat-Fys-Medd-52(2006)263

Materials sensitivity

Pure Crystalline metals

1988. Defect annealing in Ni, A. Iwase et al., 1987 Phys. Rev. Lett. 58, p.2450
1989. Defect creation in Fe, A. Dunlop et al. C. R. Acad Sci., Paris II, 309, p.1277
1993. Damage in Bi, C. Dufour et al., J. Phys.: Condens. Matter 5, p.4573

Damage efficiency :Measured number of defects divided by the number of dpa calculated at 0 K



Fe: Dunlop et al. Nucl. Instr. Meth. B90(1994)330
Bi (20 K): Dufour et al. J. Phys. Condens. matt. 5(1993)4573
Bi (100K): Dufour EuroPhys. Lett. 45(1999)585

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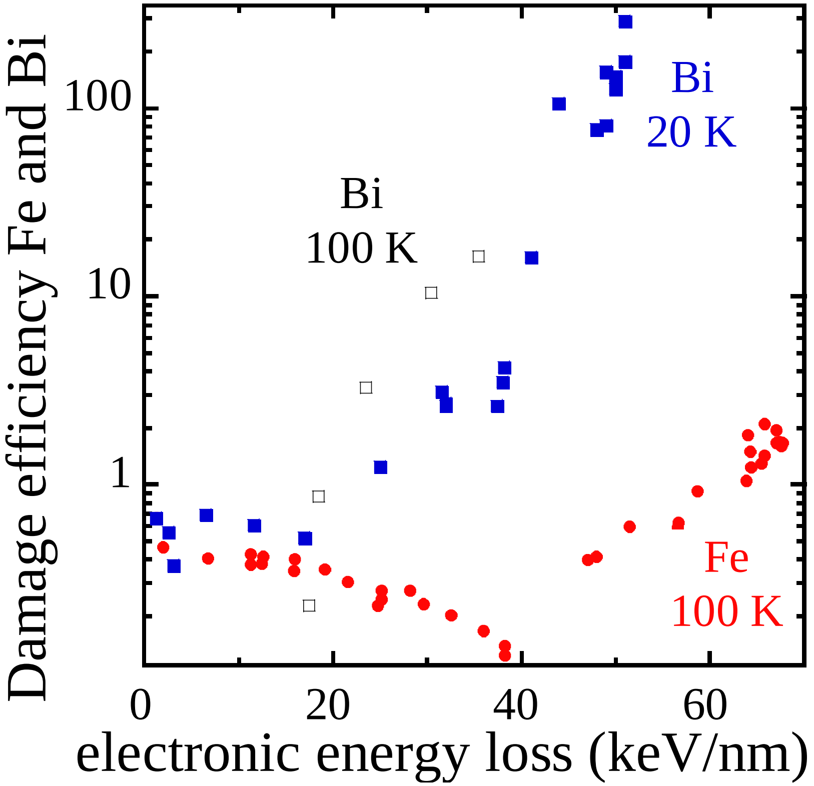

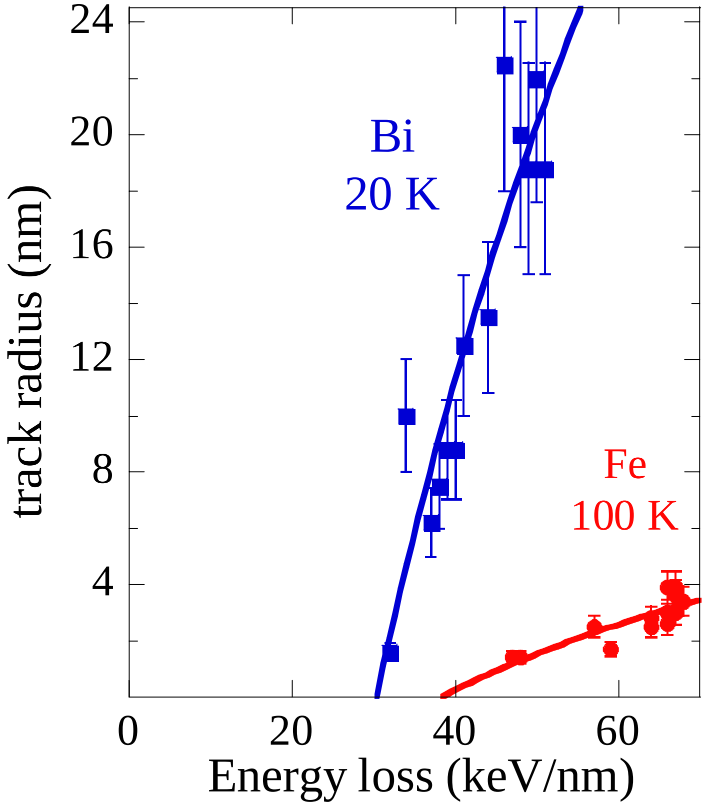

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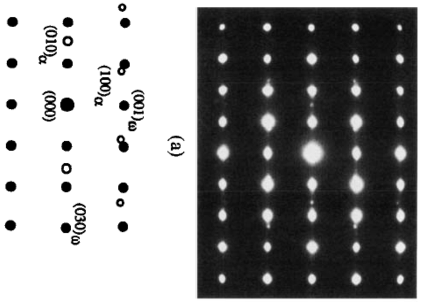
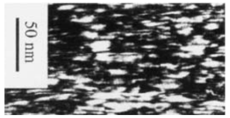
1989. Defect creation in Fe, A. Dunlop et al. C. R. Acad Sci., Paris II, 309, p.1277

1993. Damage in Bi and the inelastic thermal
spike model, C. Dufour et al.,
J. Phys.: Condens. Matter 5, p.4573

2002. Ω-phase in individual latent tracks in α-Ti
with C60 beam
M. Angiolini et al. Phil. Mag. Lett. 82, p. 81

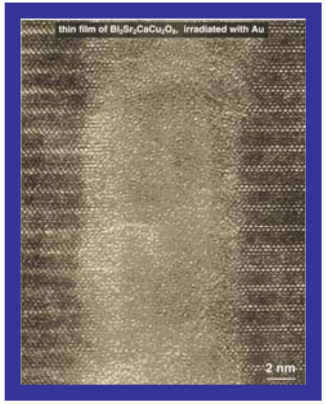




2003. Sputtering in metals and synergy
between nuclear and electronic energy losses
Mieskes et al. Phys. Rev. B67, p.155414.

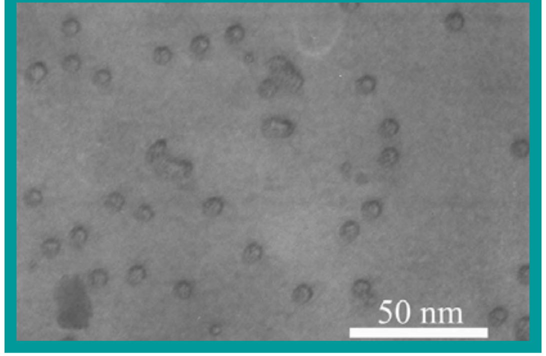
Track induced by swift heavy ions

$Bi_2Sr_2CaCu_2O_8$



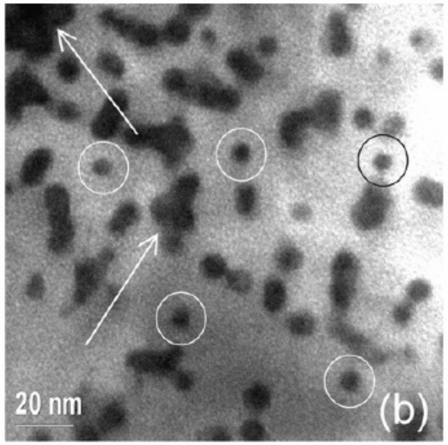
Wiesner et al.
Physica C268(1996)161

Graphite



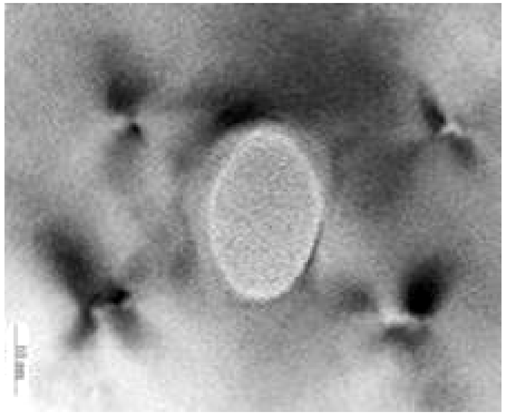
Dunlop et al. Phys. Rev.
76(2007)155403

InP

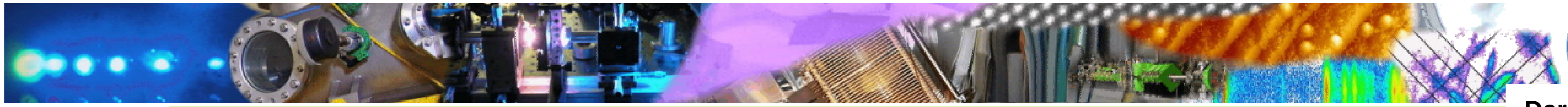


Wesch et al. NIMB 257 (2007) 283

GeS

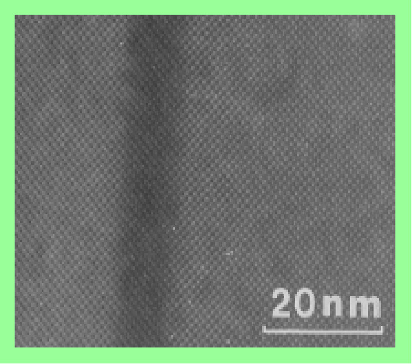


Vetter, NIMB 141(1998)



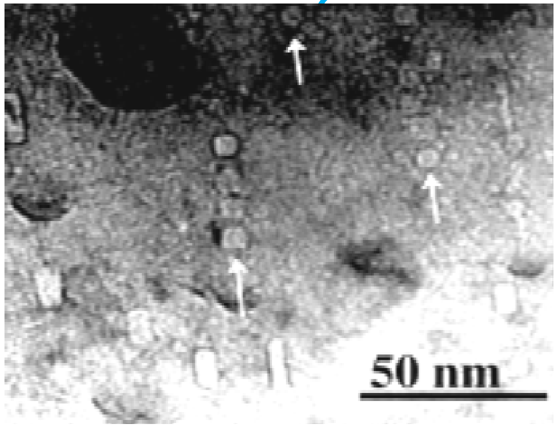
Track induced by swift heavy ions

$Y_3Fe_5O_{12}$



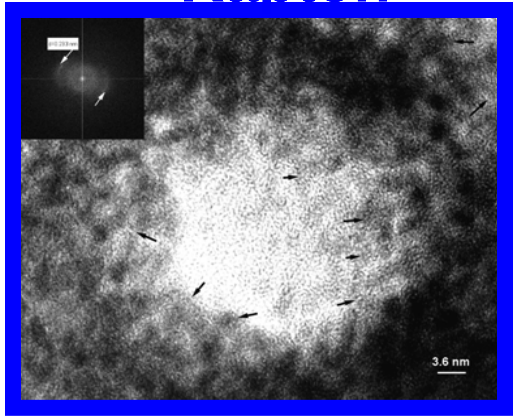
Toulemonde and Studer
Phil. Mag. A58(1988)799

CaF_2



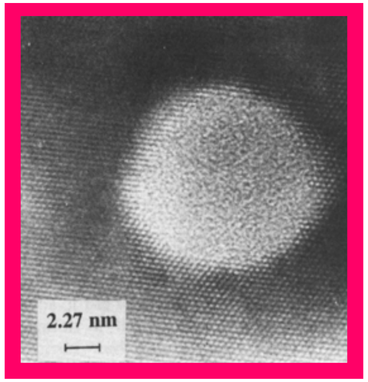
Jensen, NIMB 146 (1998)753

Kapton



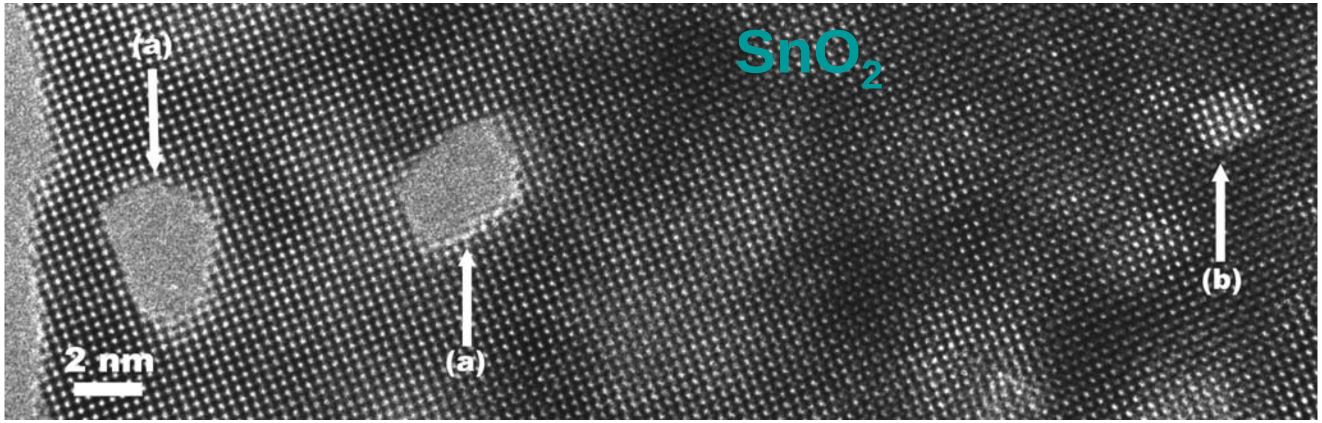
Adla et al. NIMB 185(2001)210

α-SiO_2 quartz



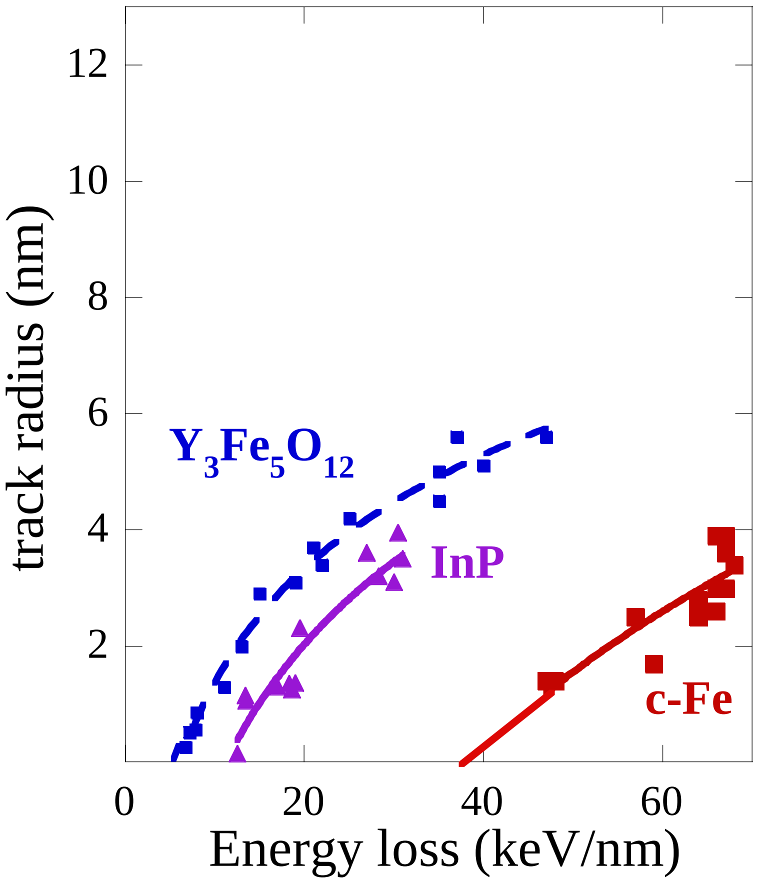
Meftah et al. Phys.Rev. B49(1994)12457

SnO_2



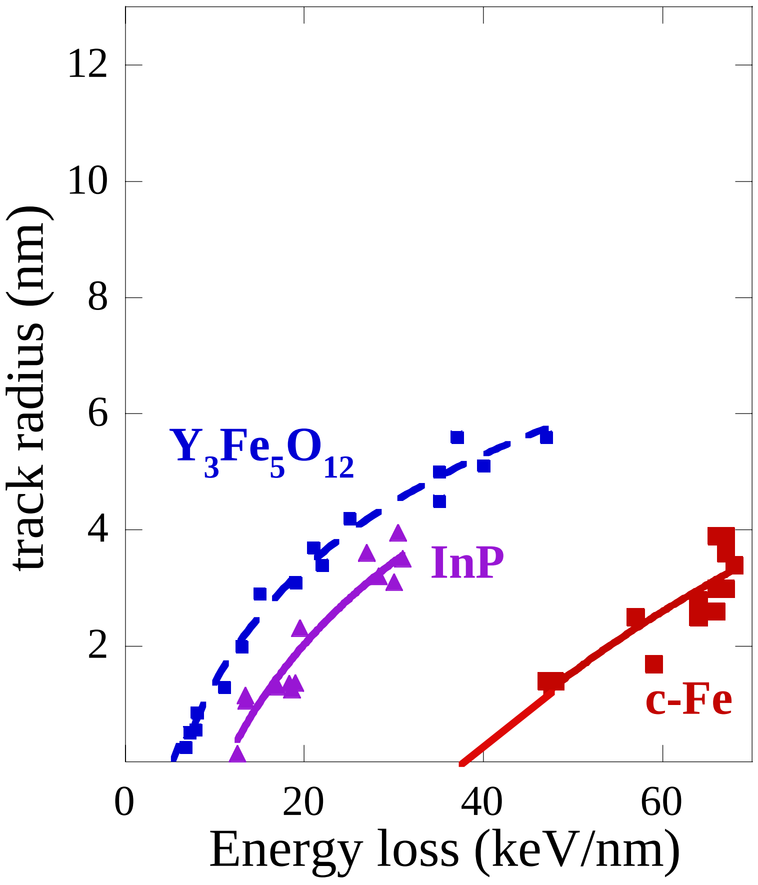
Berthelot et al. Phil. Mag. 80(2000)2257

Track formation in bulk



$Y_3Fe_5O_{12}$	Meftah et al. Phys. Rev. B48(1993)920
InP	Wesch et al. Nucl. Instr. Meth. B257(2007)283
c-Fe	Dunlop et al. Nucl. Instr. Meth. B90(1994)33

Track formation in bulk



$Y_3Fe_5O_{12}$	**Meftah et al. Phys. Rev. B48(1993)920**
InP	**Wesch et al. Nucl. Instr. Meth. B257(2007)283**
c-Fe	**Dunlop et al. Nucl. Instr. Meth. B90(1994)33**

insulators

YES polymers, ionic crystals, oxydes (**SiO_2**), etc…

semiconductors

YES GeS, InP, $Si_{0.5}Ge_{0.5}$

NO Si >26[?], Ge >30 keV/nm

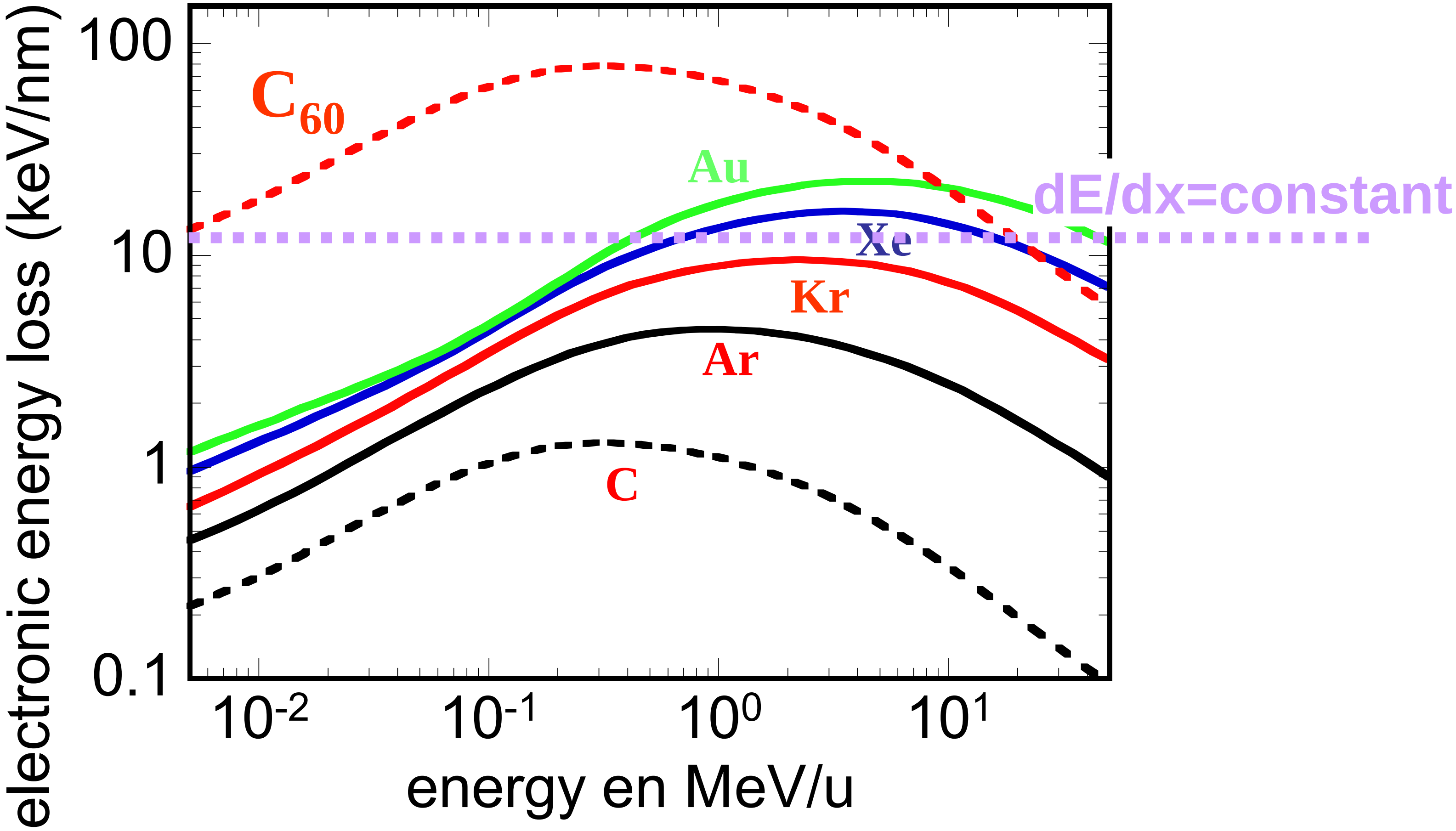
metals

YES Fe, **Bi**, Ti, Co, Zr

NO Cu, Ag, Pt, **Ni**, Nb

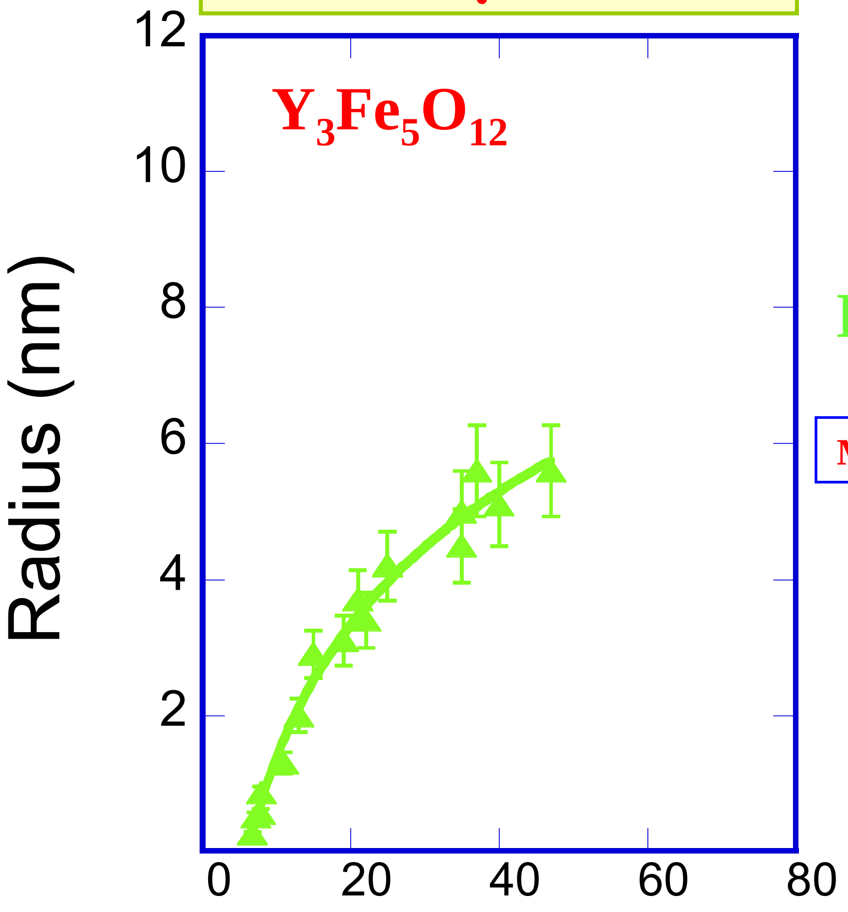
Our master curves: Energy deposition

Velocity effect



SRIM and TRIM95 J. P. Biersack et al. Nucl. Instr. Meth. 174 (1980) 257

Velocity effect



Energy loss (keV/nm)

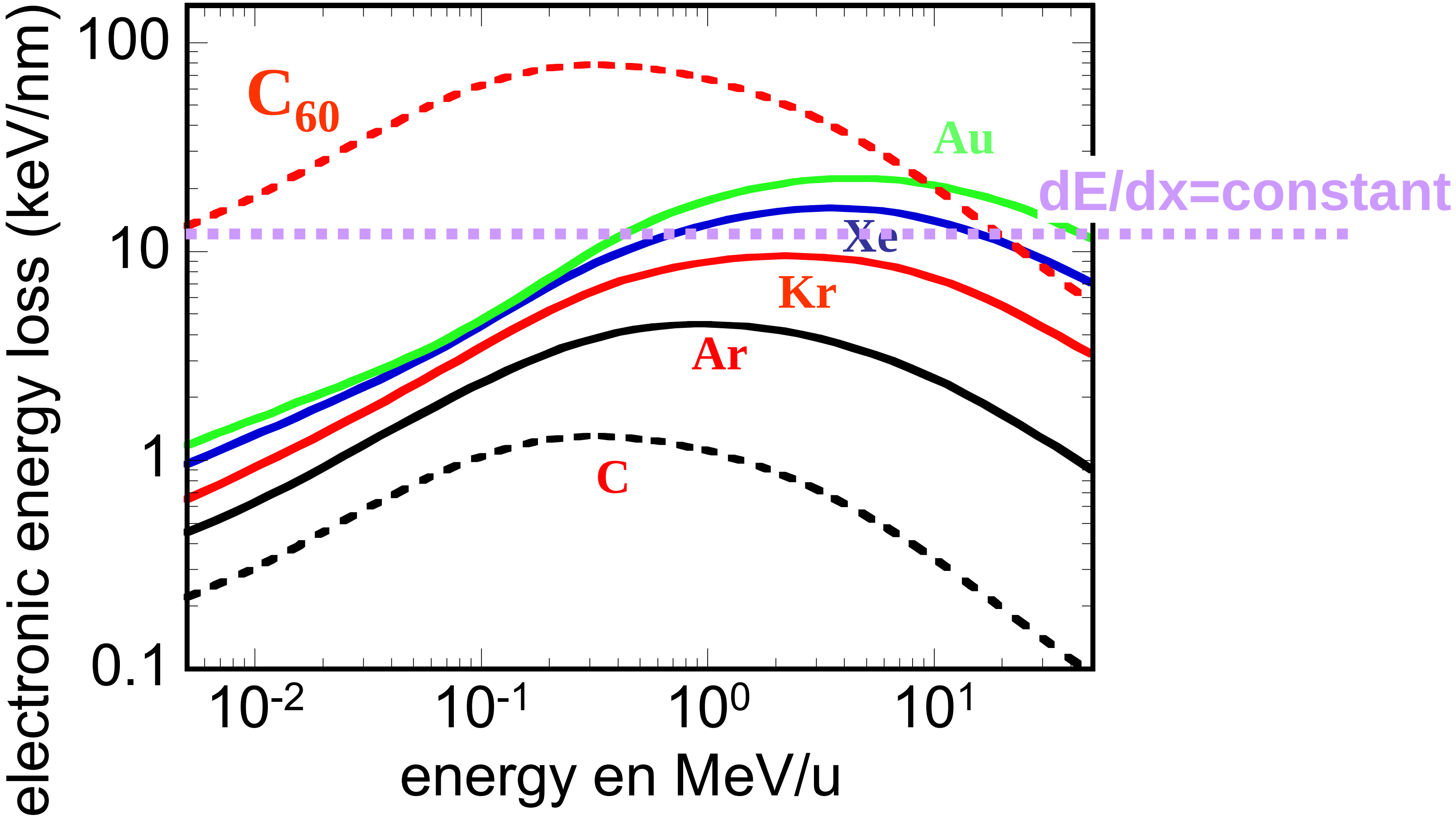
Ions at 15 MeV/u

Meftah et al. Phys. Rev. B B48(1993)920

Deposited energy density

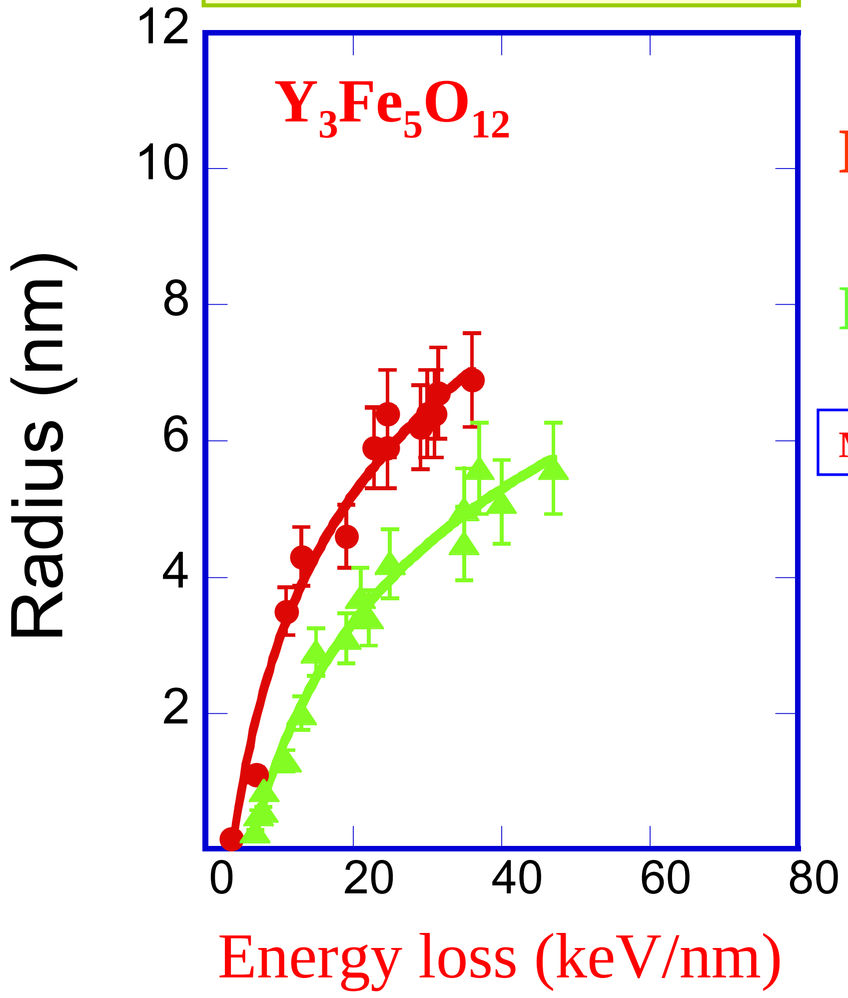
MeV/u	15
α_R (nm)	6
eV/at	1.2

Velocity effect



SRIM and TRIM95 J. P. Biersack et al. Nucl. Instr. Meth. 174 (1980) 257

Velocity effect



Ions at 1 MeV/u

Ions at 15 MeV/u

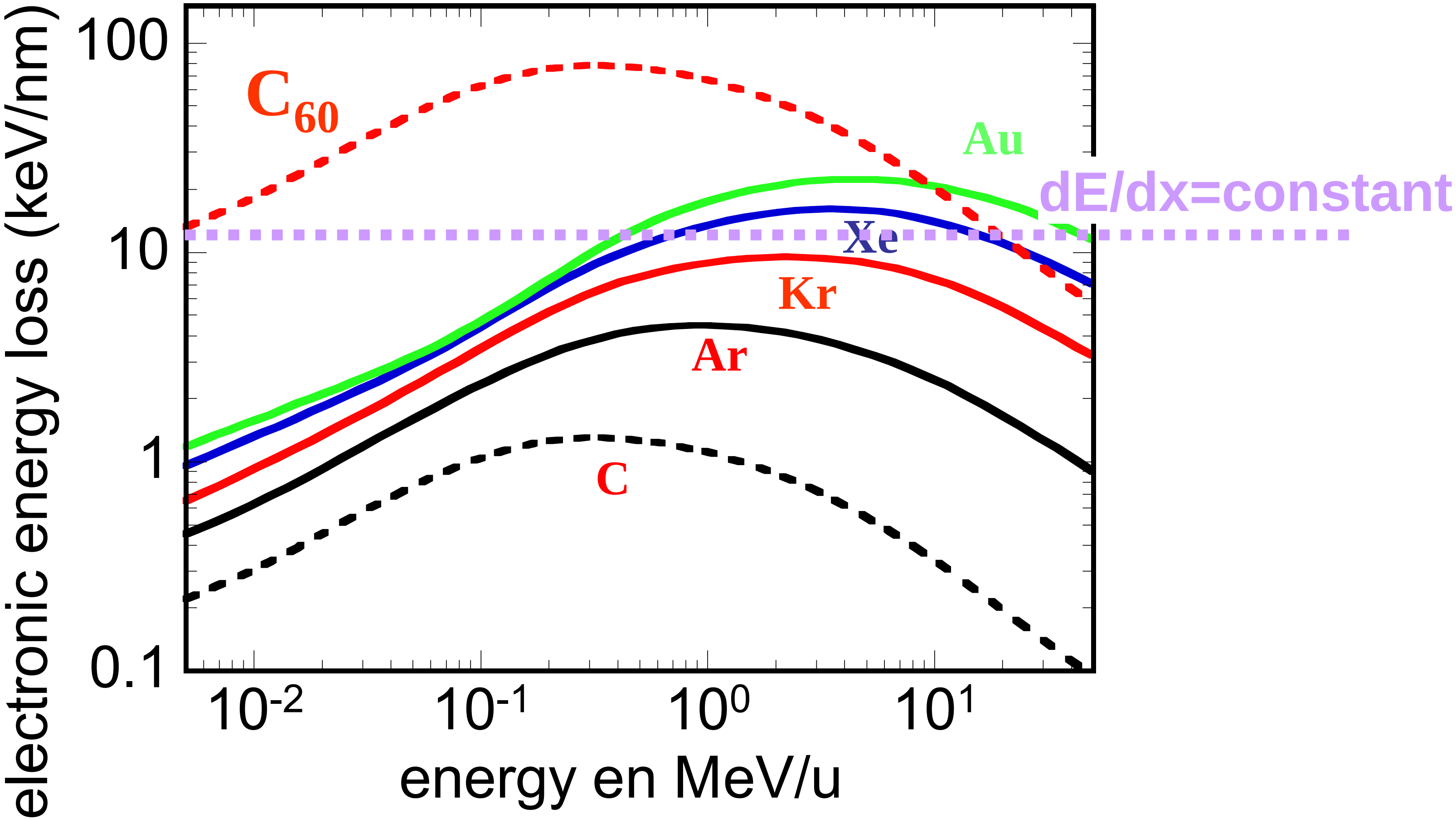
Meftah et al. Phys. Rev. B B48(1993)920

Deposited energy density

MeV/u	15	**1**
α_R (nm)	6	**2**
eV/at	1.2	**11**

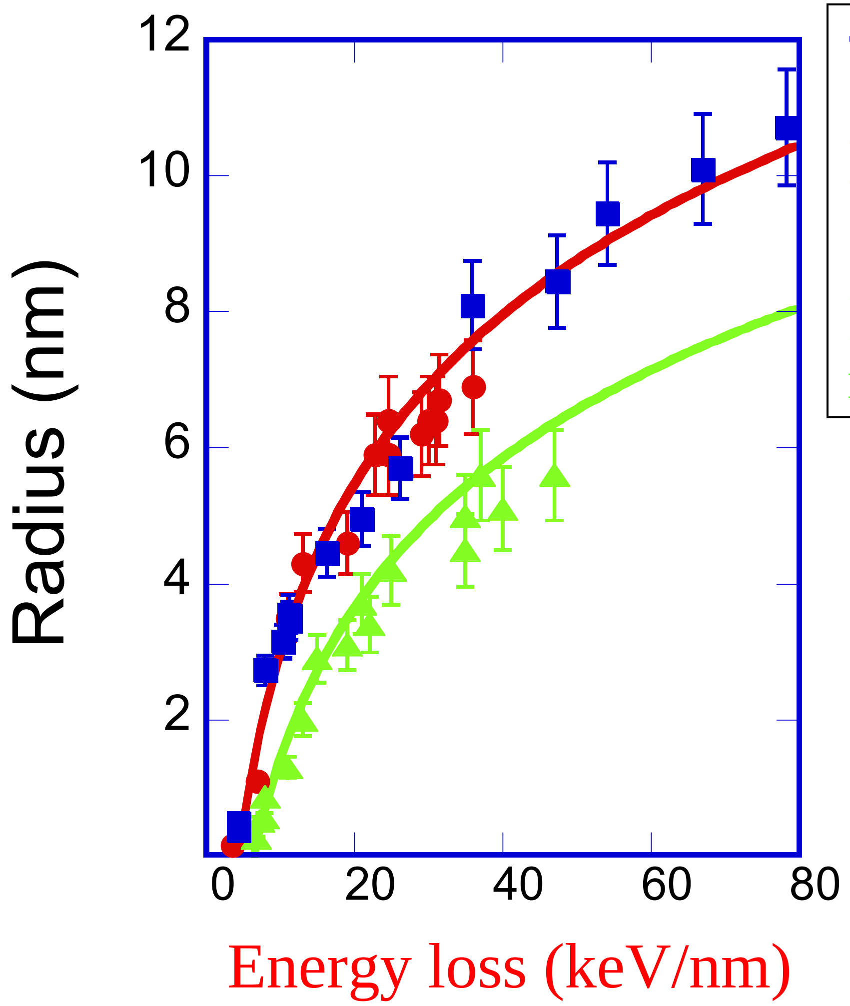
Energy loss threshold goes from **7 to 4 keV/nm** from **15 to 1 MeV/u**

Velocity effect



SRIM and TRIM95 J. P. Biersack et al. Nucl. Instr. Meth. 174 (1980) 257

Velocity effect



Jensen et al. Nucl. Instr. Meth. 146(1998)412

C_{60} beam (~0.05 MeV/u)

Ions at 1 MeV/u

Ions at 15 MeV/u

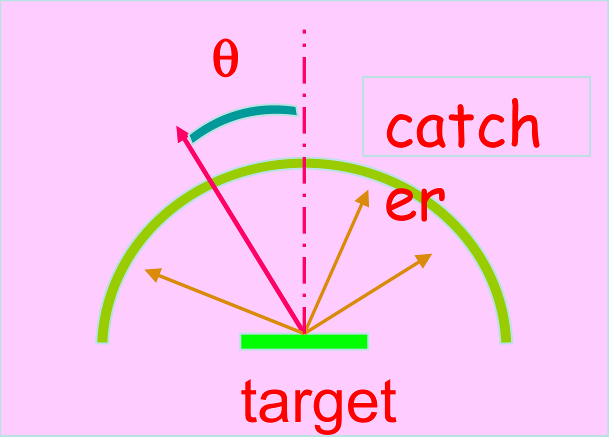
Meftah et al. Phys. Rev. B B48(1993)920

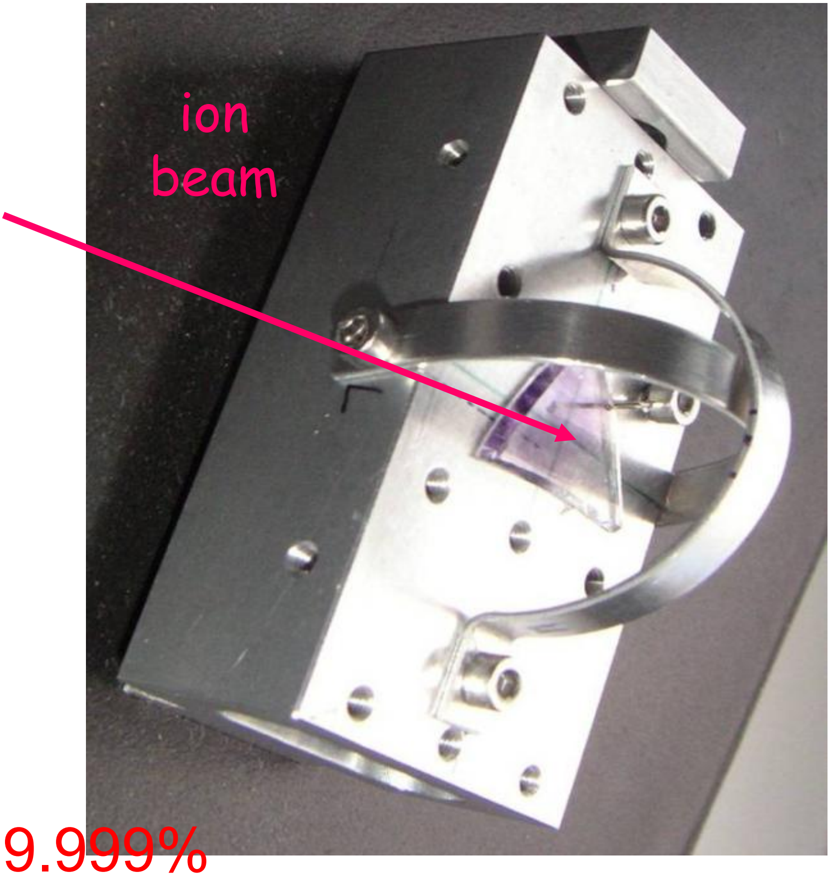
Deposited energy density
for dE/dx=15 keV/nm

MeV/u	15	1	**0.07**
α_R (nm)	6	2	**0.6**
eV/at	1.2	11	**120**

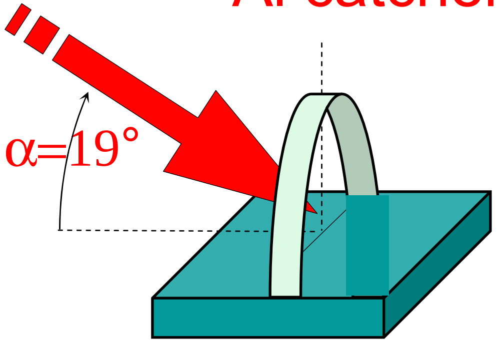
Correlation between track and sputtering ???

1. Scheme





Al catcher (20 µm) at 99.999%



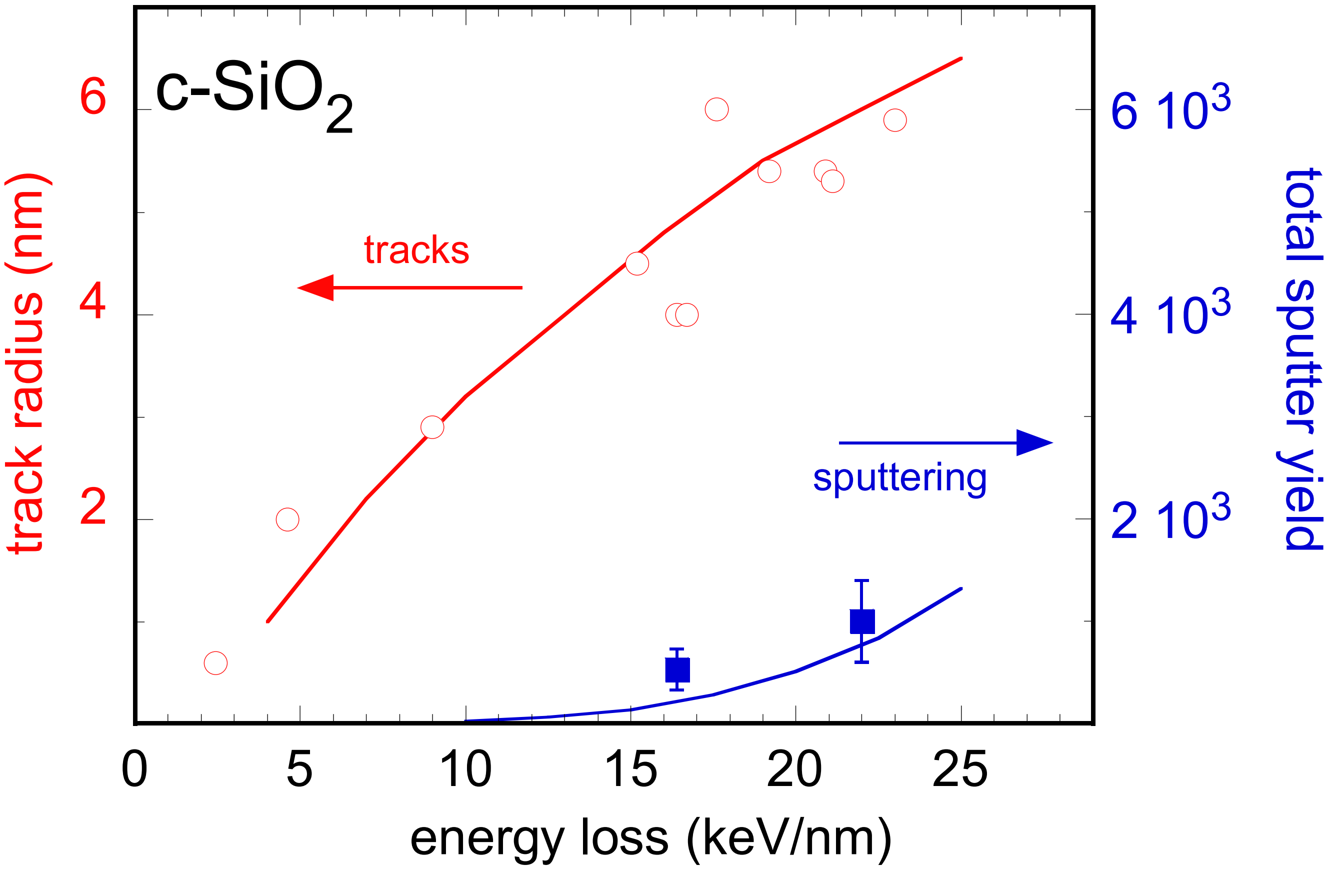
sample and catcher arcs

Flux 10^{10}p/cm^2/s

Fluence 10^{12}p/cm^2

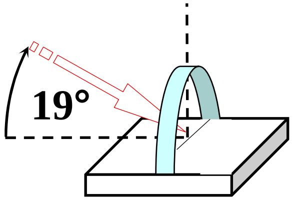
SiO_2 Quartz

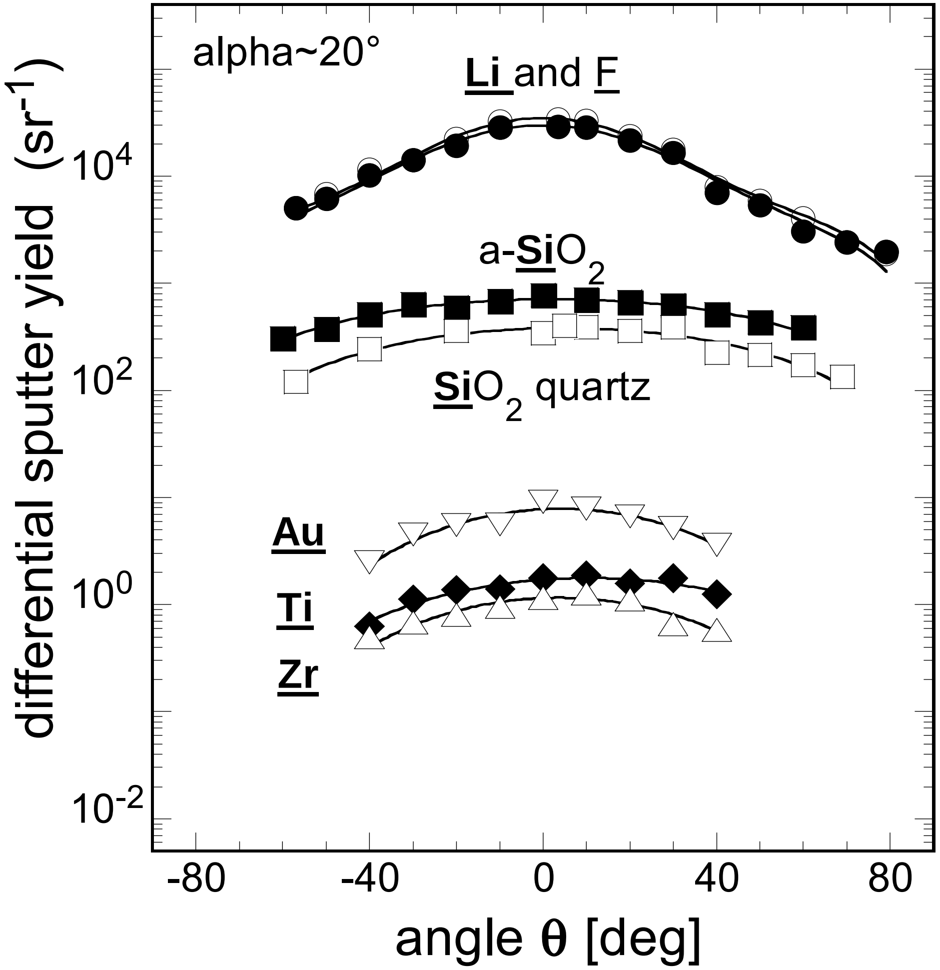
tracks and sputtering



Meftah et al. Phys. Rev. B 49(1994)12457
Toulemonde, Assmann, Trautmann, Grüner Phys. Rev. Lett. 88(2002)057602

Sputtering



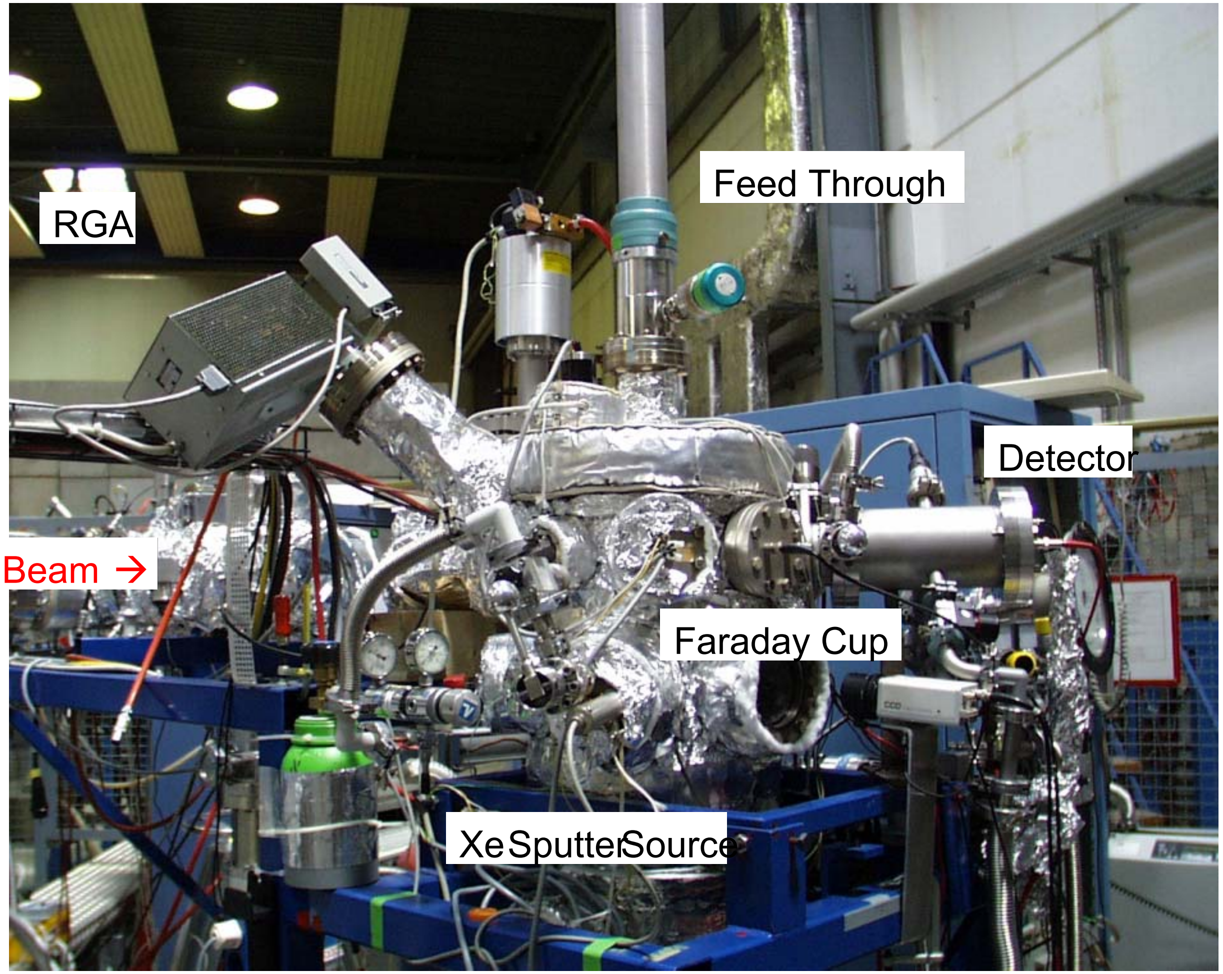


Assmann et al. Top. Appl. Phys. 110(2007)401,

Toulemonde et al. Nucl. Instr. Meth. B212 (2003) 346

Trautmann et al. Nucl. Instr. Meth. 164/165(2000365

Desorption of surface molecules

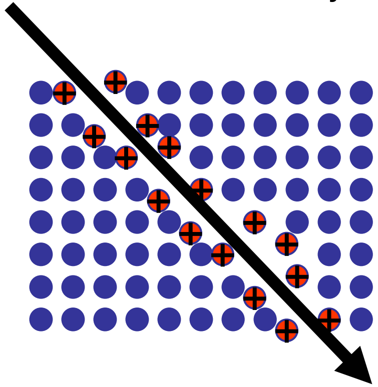


collision system	experiment
1.4 MeV/u Xe --> **Cu**	290...360
1.4 MeV/u Xe --> **Au**	90
1.4 MeV/u Xe --> **Rh**	915...1286
1.4 MeV/u Xe --> Cu_2O	1530
1.4 MeV/u C --> Cu	10
1.4 MeV/u Cr --> Cu	150
1.4 MeV/u Pb --> Cu	800
4.2 MeV/u Pb --> Au	800

Bender et al. Nucl. Instr. Meth. B 267(2009)885

Track formation models

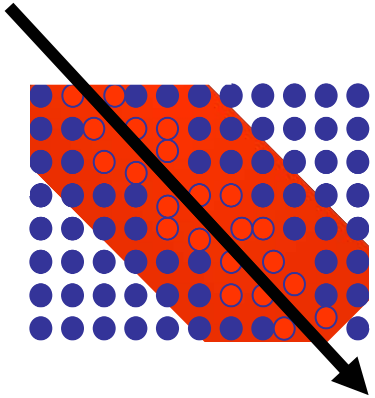
macroscopic



Coulomb explosion: screening by return electrons (~10^{-13} s)

Few qualitative descriptions

[Fleischer et al. J. Appl. Phys. 36(1965)3645]
[Lesueur and Dunlop Rad. Eff. Def. Sol. 126(1993)135]
[Schiwietz et al. Phys. Rev. lett. 69(1992)628]
[Rosmej et al. SHIM 2008 neutralisation in 10^{-14} s]

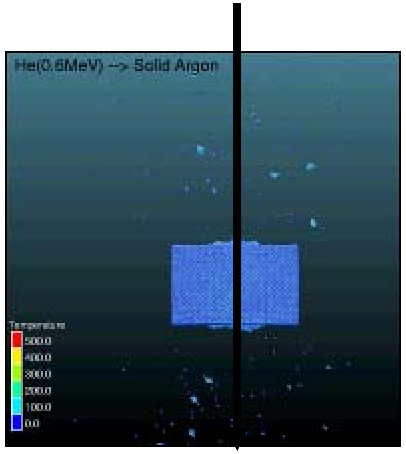


Thermal spike: energy deposited on electrons, electron-phonon coupling
local melting and quenching

transient thermal processes

[Seitz and Köhler Sol. St; Phys. 2(1956)305]
[Lifshitz et al.J. Nucl. Ener. A12(1960)69]
[Dufour et al. J. of Phys. Cond. Matt. 5 (1993)4573]

microscopic



Molecular Dynamic calculations: ab initio lattice calculations

Interatomic potential

Large computer times

[Urbassek et al. Phys. Rev. B49(1994)786]

continuous electron subsystem included

[Beuve et al. Phys. Rev. B68(2003)125423]
[Kluth et al. Phys. Rev. Lett. 101(2008)175503]

Inelastic thermal spike (**i-TS**)
or ‘ two temperatures ’ Model

[Seitz and Köhler Sol. St. Phys. 2(1956)305, Lifshitz et al. J. Nucl. Energy A12(1960)69]

Electrons
$$C_e(T_e)\frac{\partial T_e}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[rK_e(T_e)\frac{\partial T_e}{\partial r}\right]-g(\underline{T_e}-T_a)+A(r[\alpha_R],t)$$

Atoms
$$C_a(T_a)\frac{\partial T_a}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[rK_a(T_a)\frac{\partial T_a}{\partial r}\right]+\underline{g}(T_e-T_a)$$

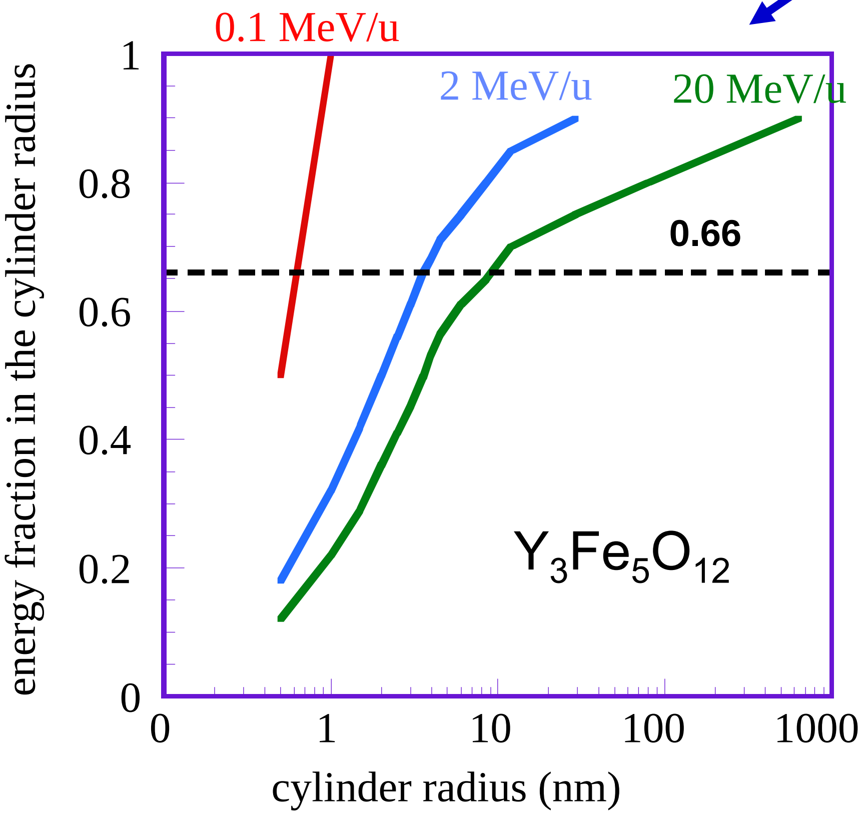
Electron-phonon coupling

Metals
Dufour et al. J. of Phys.:Condens. Matt. 5(1993)4573
Wang et al. J. of Phys.:Condens. Matt. 6(1994)6733,7(1995)2525
Insulators
Toulemonde et al. Nucl. Instr. Meth. B166-167(2000)903 and Meftah et al. Nucl. Instr. Meth. B 237(2005)563
Toulemonde et al. Mat-Fys-Medd-52(2006)293
Critical examination:
Klaumünzer Mat-Fys-Medd-52(2006)293

Energy generation on electrons

[Waligorski et al. Nucl. Tracks Rad. Meas. 11(1986)309, B. Gervais PhD Thésis(1994), Caen]

$$C_e(T_e)\frac{\partial T_e}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[rK_e(T_e)\frac{\partial T_e}{\partial r}\right]-g(T_e-T_a)+A(\underline{r[\alpha_R],t)}$$



LATTICE PARAMETERS

ELECTRON SUBSYSTEM

$$C_e(T_e)\frac{\partial T_e}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[rK_e(T_e)\frac{\partial T_e}{\partial r}\right]-g(T_e-T_a)+B(r,t)$$

LATTICE SUBSYSTEM

$$\underline{C_a(T_a)}\frac{\partial T_a}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[\underline{rK_a}(T_a)\frac{\partial T_a}{\partial r}\right]+g(T_e-T_a)$$

- Lattice specific heat $C_a(T_a)$
- lattice thermal conductivity $K_a(T_a)$
  whatever it is an insulator or a metal
- Melting temperature and latent heat of fusion :
  energy necessary to melt
- Vaporisation temperature and the latent heat of vaporisation
  energy necessary to vaporize
  =Sublimation energy U_s

from experimental measurements at equilibrium

Parameters for electron energy diffusion:
Quasi-free electron gas model: Au metal as reference

Dufour et al. and Wang et al., J. Phys. Condens. Matter (1993 and 1994)

$$C_e(T_e)\frac{\partial T_e}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rK_e(T_e)\frac{\partial T_e}{\partial r}\right] - g(T_e - T_a) + A(r[\alpha_R],t)$$

Electronic specific heat :

$C_e(T_e) = \gamma T_e$ $\gamma = n_e(\pi^2 k_B{}^2/2\varepsilon_F)$

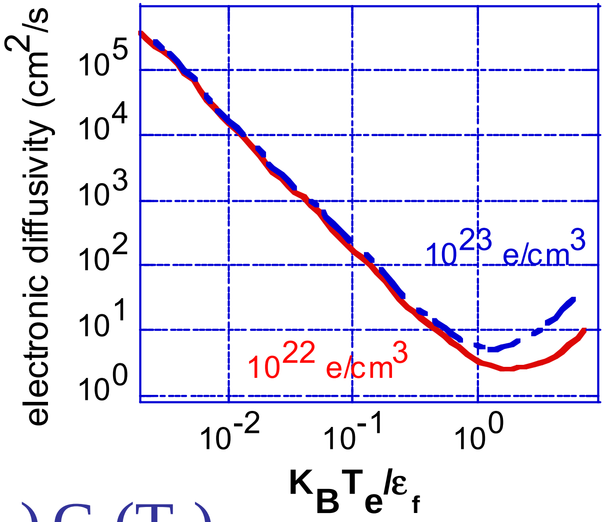
ε_F Fermi energy

k_B Boltzmann constant

n_e the number of valence electrons

$C_e(T_e) = 1.5\, n_e k_B$ for $T_0 > 1.5\, n_e k_B/\gamma$

Electronic diffusivity :



[Martynenko and Yavlinskii Sov. Phys. -Dokl28(1983)39]

$D_e = 0.33\,(v_F{}^2\, m_e)/(n_e e^2 \rho)$

v_F Fermi velocity,

m_e effective mass of electrons

e electron charge

ρ electrical resistivity of Au

Electronic thermal conductivity : $K_e(T_e) = D_e(T_e)\, C_e(T_e)$

Electron phonon coupling for metals

Kaganov et al. Sov. Phys. JETP(1957)173 and Allen Phys. Rev. Lett. 59(1987)1460
Dufour et al. Nucl. Instr. Meth. B107(1996)218

$g \sim \pi^4 \, (k_B \, n_e \, v_s)^2 \, /(18 \, K(T_a))$

v_s sound velocity which decreases with increasing masses

$K(T_a)$ the measured thermal resistivity of the considered metal.

λ the electron mean free path

$$\lambda^2 = D(T_e)*C(T_e)/g = D(T_e)* \tau$$

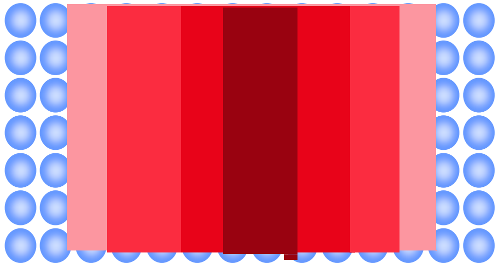
From thermal conductivity since $K(T_a)$

	Cu	[Bi]	Fe	Ti	Graphite	at 300 K
g	0.12	[0.2]	1.3	2.6	30	**10^{12} W K^{-1} cm^{-3}**
λ	34	[26]	10	7	2.2	**nm**
τ	3300	[2000]	310	150	13	**10^{-15} s**

In a first approximation g is known for crystalline metallic materials

Energy diffusion and transfert

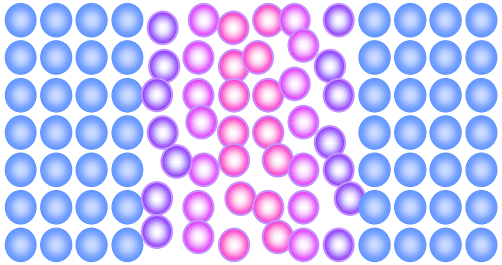
electronic subsystem



$$C_e(T_e)\frac{\partial T_e}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(rK_e(T_e)\frac{\partial T_e}{\partial r}\right)-g\cdot(T_e-T)+A(r,t)$$

electron-phonon interaction

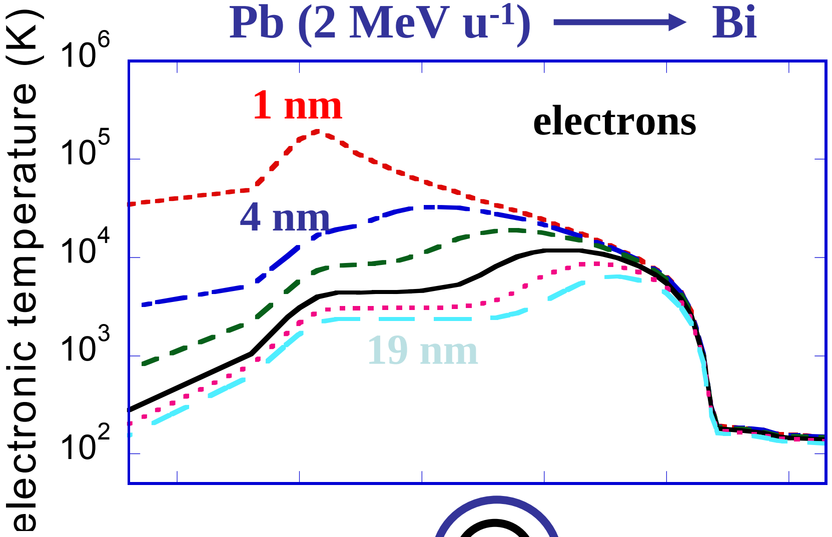
$$C(T)\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(K(T)\frac{\partial T}{\partial r}\right)+g\cdot(T_e-T)$$



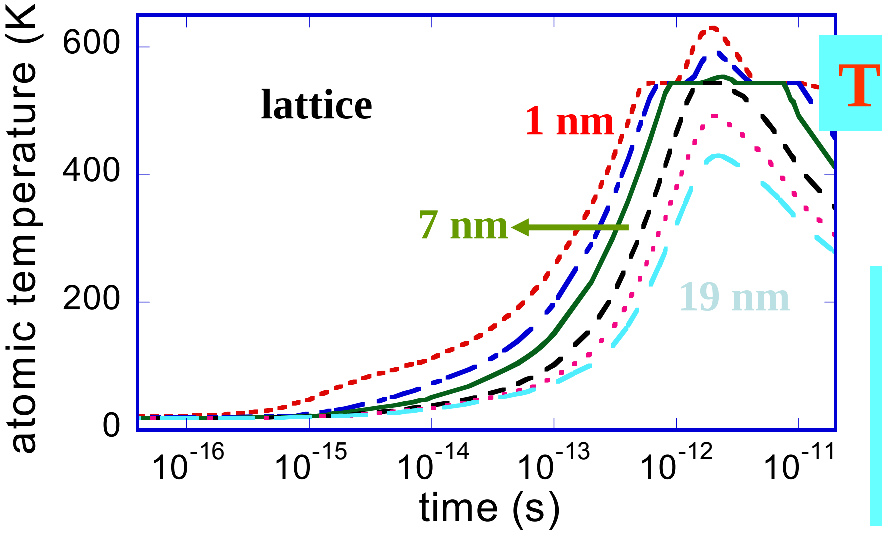
atomic subsystem

[C. Dufour et al. Euro Phys. Lett. 45(1999)585]

Pb (2 MeV u^{-1}) → Bi



$g=0.14\ 10^{12}\ \mathrm{W\ K^{-1}\ cm^{-3}}$

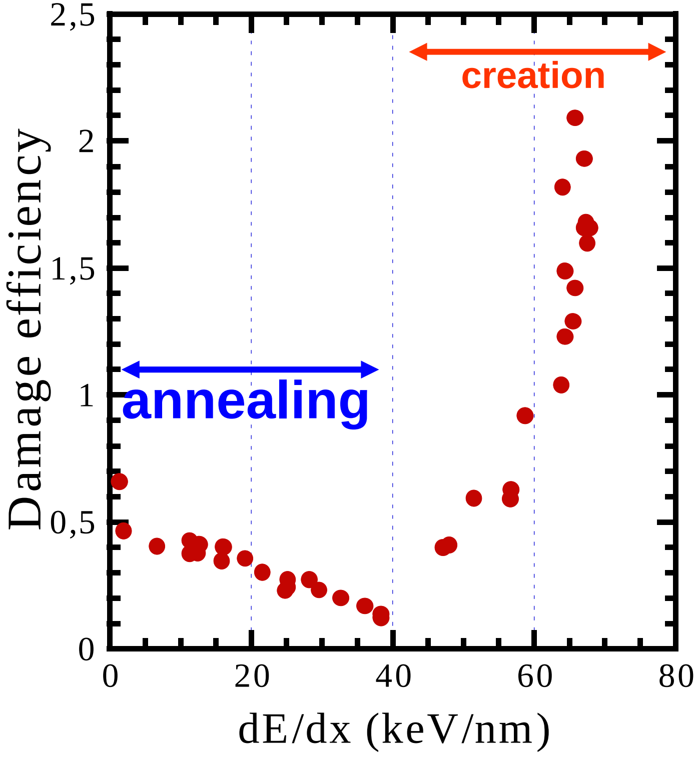


T_{melt}

Criteria ?

Defect annealing in Fe

Damage efficiency



[Dunlop et al. Nucl. Instr. Meth. B90(1994)330]

Ni

Iwase et al. Phys. Rev. Lett. 58(1987)*2450*

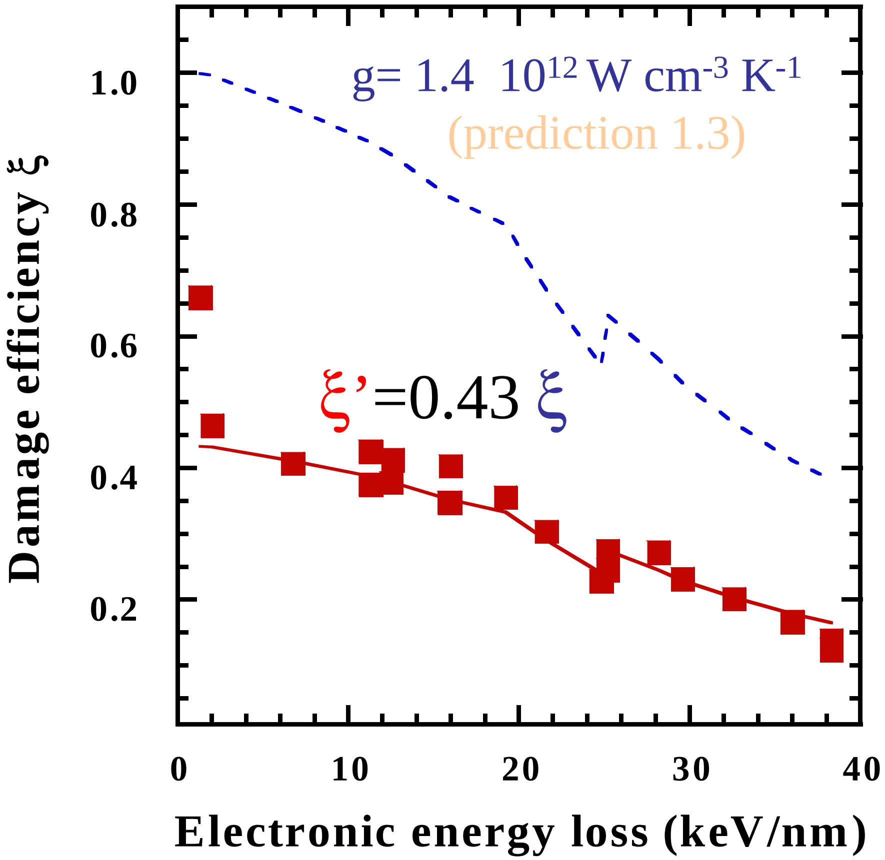
***g = 10*^{12} W K^{-1} cm^{-3}**

Probability of defect annealing:

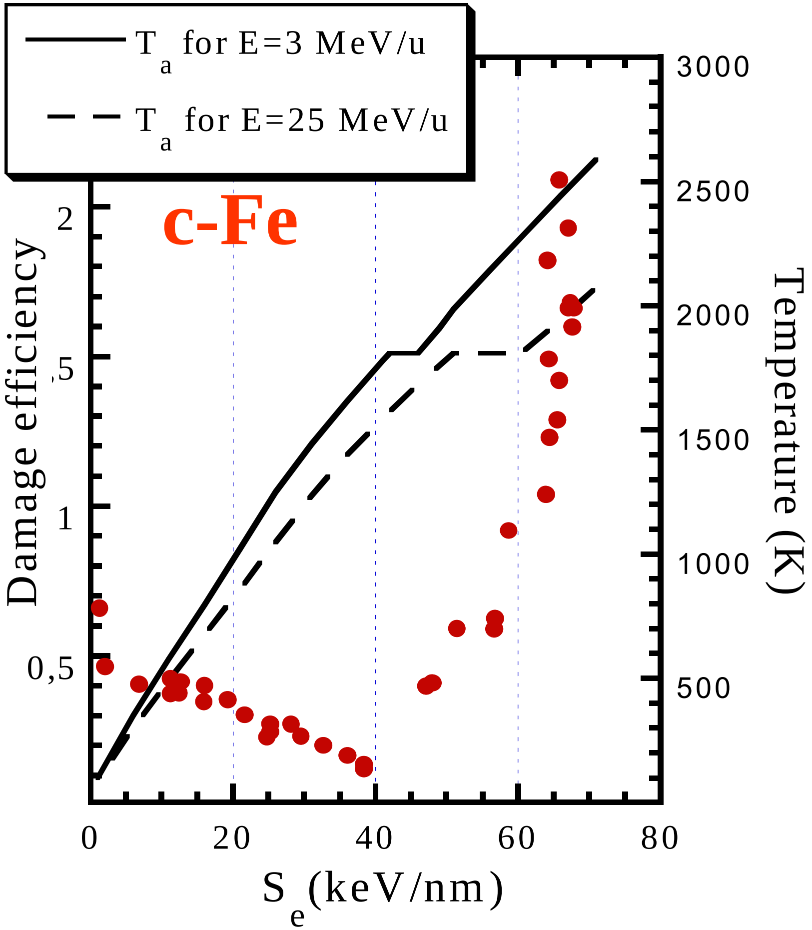
$\nu(T_a(t,r)) = \nu_0 \exp(-E/\, kT_a(t,r))$ with $\nu_0 = T_D k_B/h$

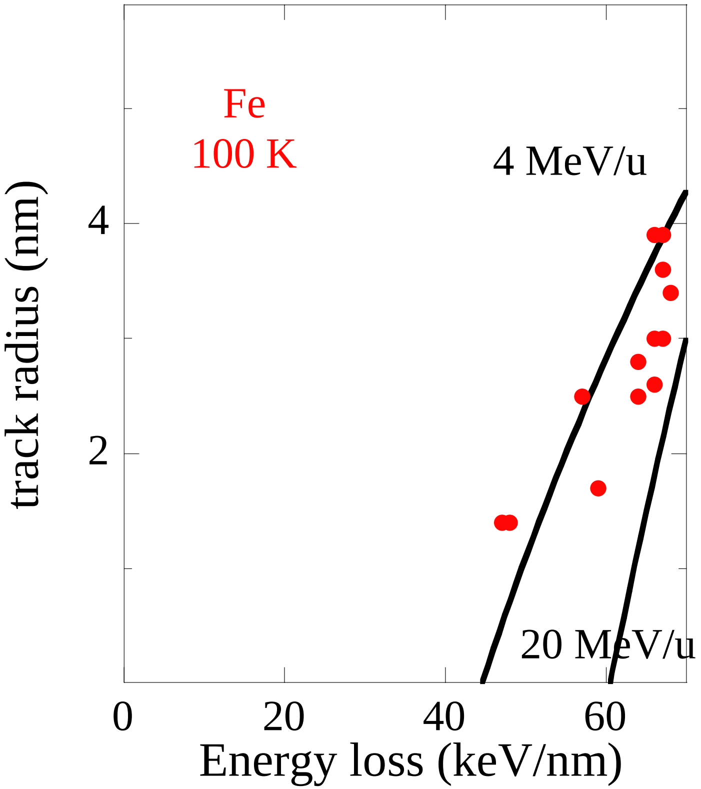
[Wang et al. Nucl. Instr. Meth. B115(1996)577]

Target: Iron at 20 K

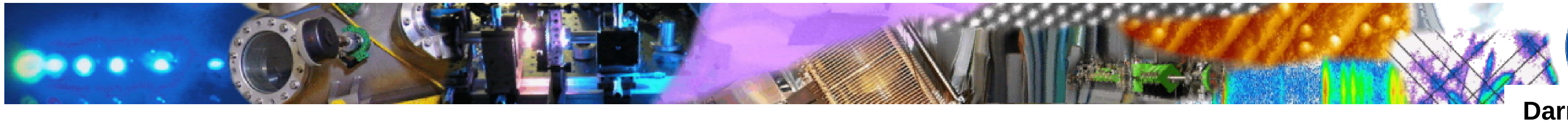


Application for **c-Fe** and **a-**$Fe_{85}B_{15}$ *(Unit of g: W* cm^{-3} *K*$^{-1}$*)*

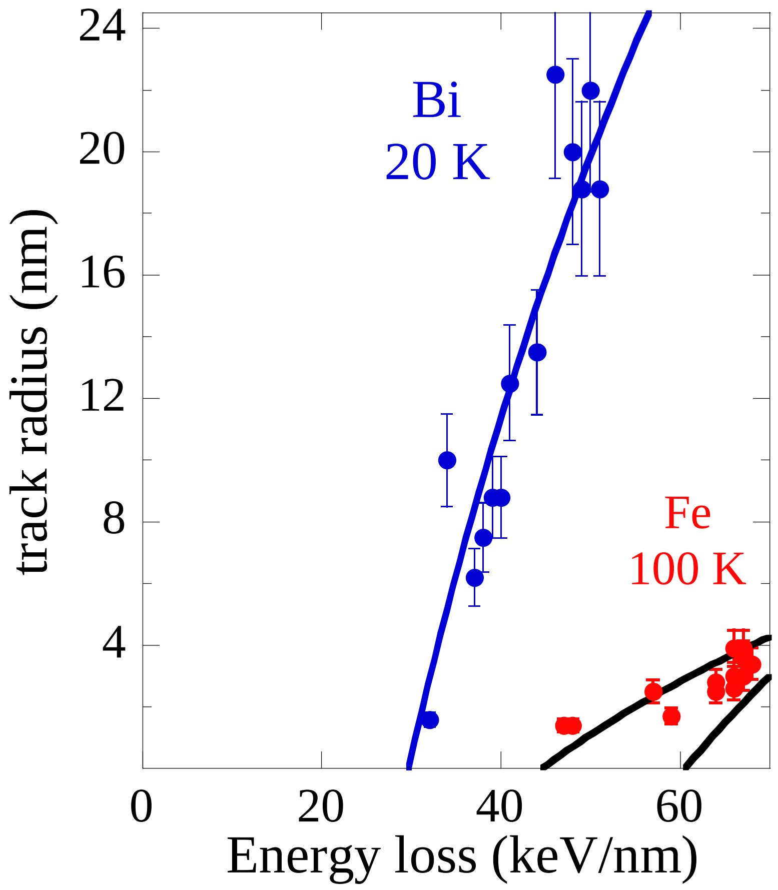




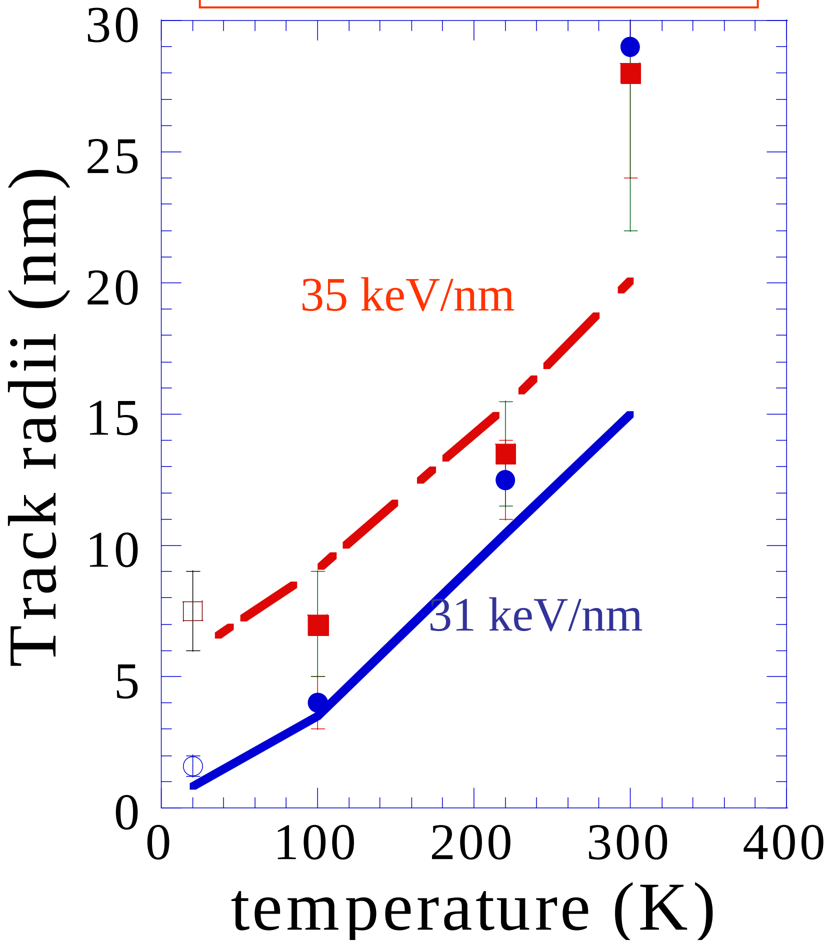
[Dunlop et al. Nucl. Instr. Meth. B90(1994)330]
[Dufour et al. Bull. Mater. Sci. 22(1999)671]



Bi theory and temperature effect



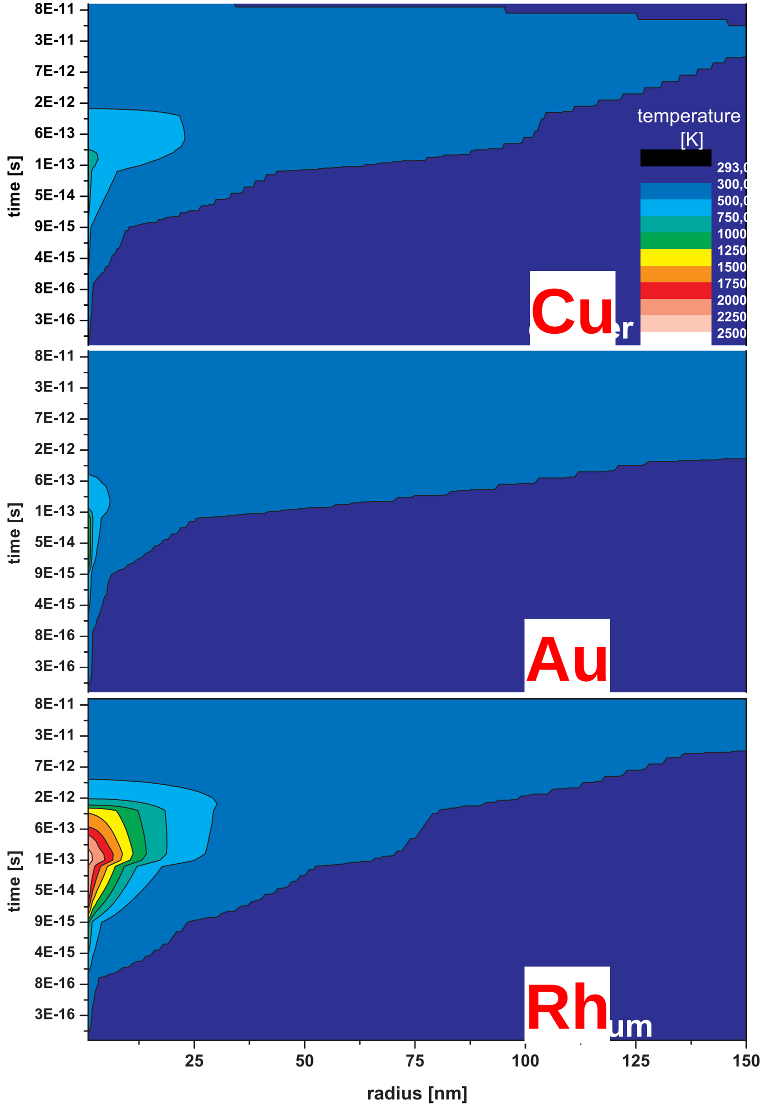
From track fitting for Bi:
$g=0.14\ 10^{12}$ ($P\ 0.20\ 10^{12}$)
Dufour et al. EPL 45(1999585



[C. Dufour et al. Euro Phys. Lett. 45(1999)585]
[Wang et al. J. Phys. : Condens. Matter 6(1994)6733]

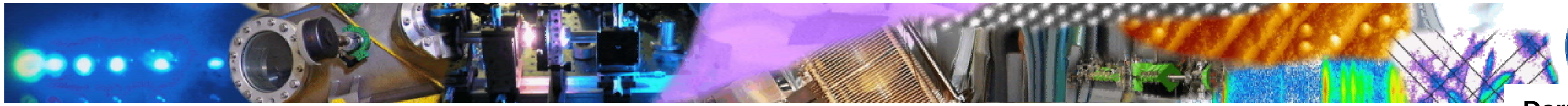
Desorption of surface molecules

Atomic temperature



collision system	experiment	calculation
1.4 MeV/u Xe --> **Cu**	290...360	185
1.4 MeV/u Xe --> **Au**	90	165
1.4 MeV/u Xe --> **Rh**	915...1286	3400
1.4 MeV/u Xe --> Cu2O	1530	10000
1.4 MeV/u C --> Cu	10	5
1.4 MeV/u Cr --> Cu	150	40
1.4 MeV/u Pb --> Cu	800	525
4.2 MeV/u Pb --> Au	800	675

Bender et al. Nucl. Instr. Meth. B to be published 2009



FOR INSULATORS

Parameters for electron energy diffusion:

As suggested by **[Katin et al. Sov. Techn. Phys. Lett. 13(1987)276]**
Hot electrons in the conduction band of an insulator
behave like hot electrons in metals

Electronic specific heat : $C_e(T_e) = 1 \text{ J cm}^{-3} \text{ K}^{-1}$

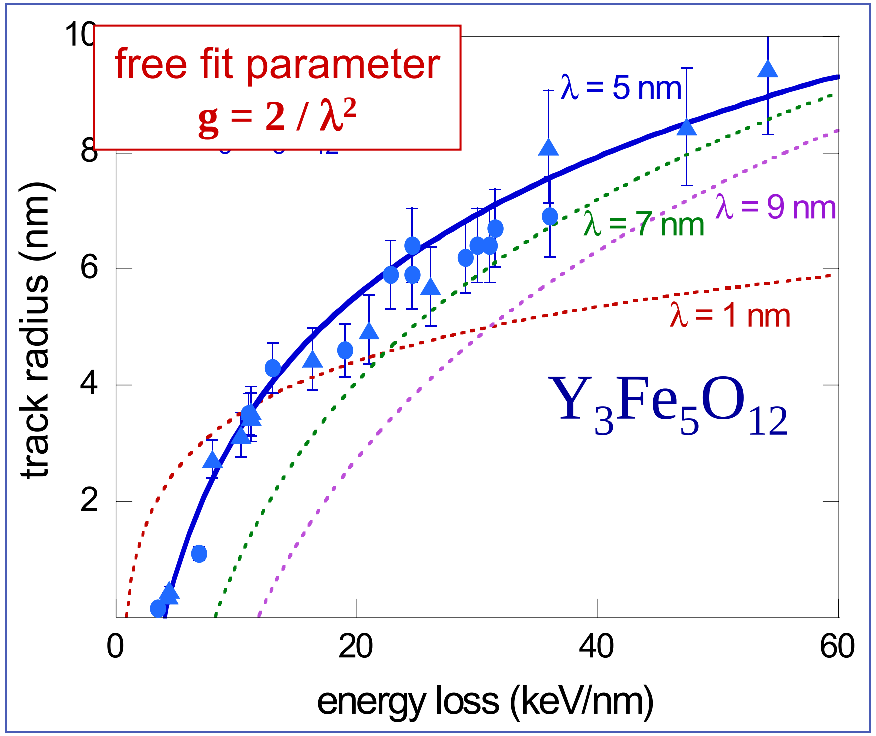
Thermal diffusivity: $D_e(T_e) = 2 \text{ cm}^2 \text{ s}^{-1}$

Electronic thermal conductivity : $K_e(T_e) = D_e(T_e)\, C_e(T_e) = 2 \text{ W cm}^{-1} \text{ K}^{-1}$

Electron phonon mean free path: $\lambda^2 = 2/g$
λ will be the free parameter
and electrons cooling is inhibited when $T_a > T_e$

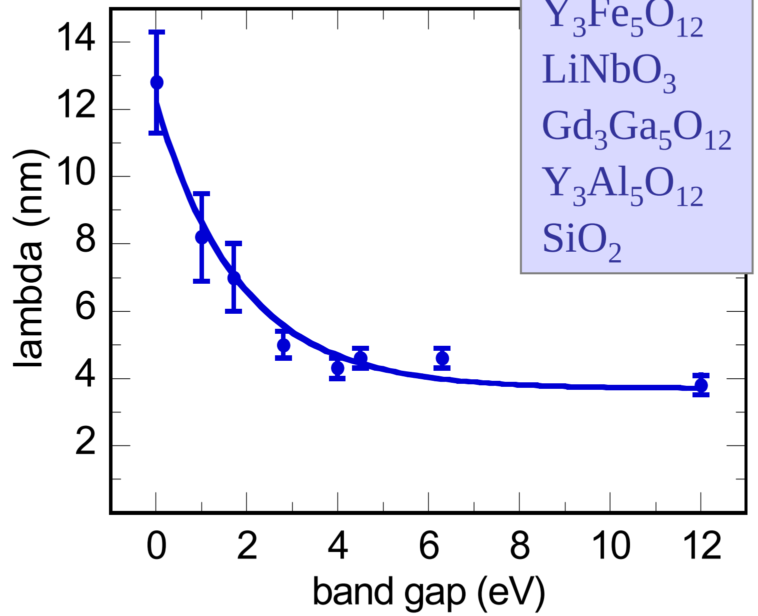
Thermal spike in insulators

Electron-phonon mean free path



free fit parameter

$g = 2 / \lambda^2$

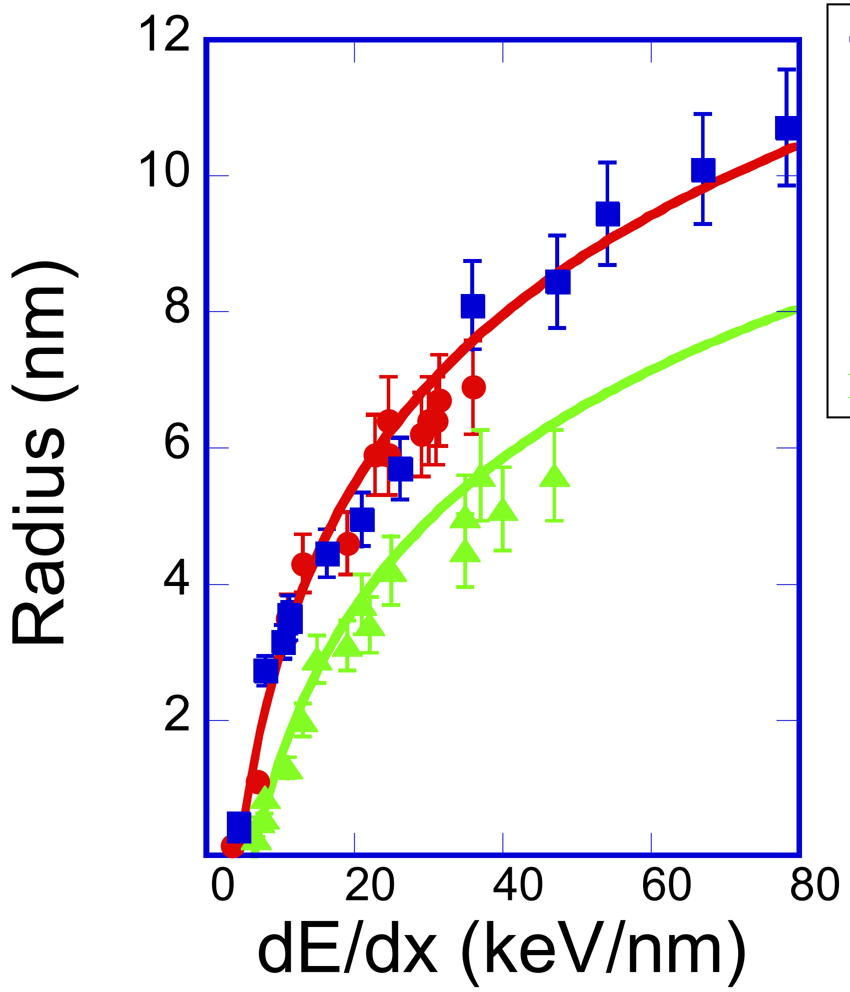


High T_c
$BaFe_{12}O_{19}$
GeS
$Y_3Fe_5O_{12}$
$LiNbO_3$
$Gd_3Ga_5O_{12}$
$Y_3Al_5O_{12}$
SiO_2

Electron-phonon mean free path λ scales with band gap

Meftah et al. Nucl. Instr. Meth. B237(2005)563
Toulemonde et al. Nucl. Instr. MethB166/167(2000)903

Velocity effect in $Y_3Fe_5O_{12}$



Jensen et al. Nucl. Instr. Meth. 146(1998)412

C_{60} beam (~0.05 MeV/u)

Ions at 1 MeV/u

Ions at 15 MeV/u

Meftah et al. Phys. Rev. B B48(1993)920

From the i-thermal spike

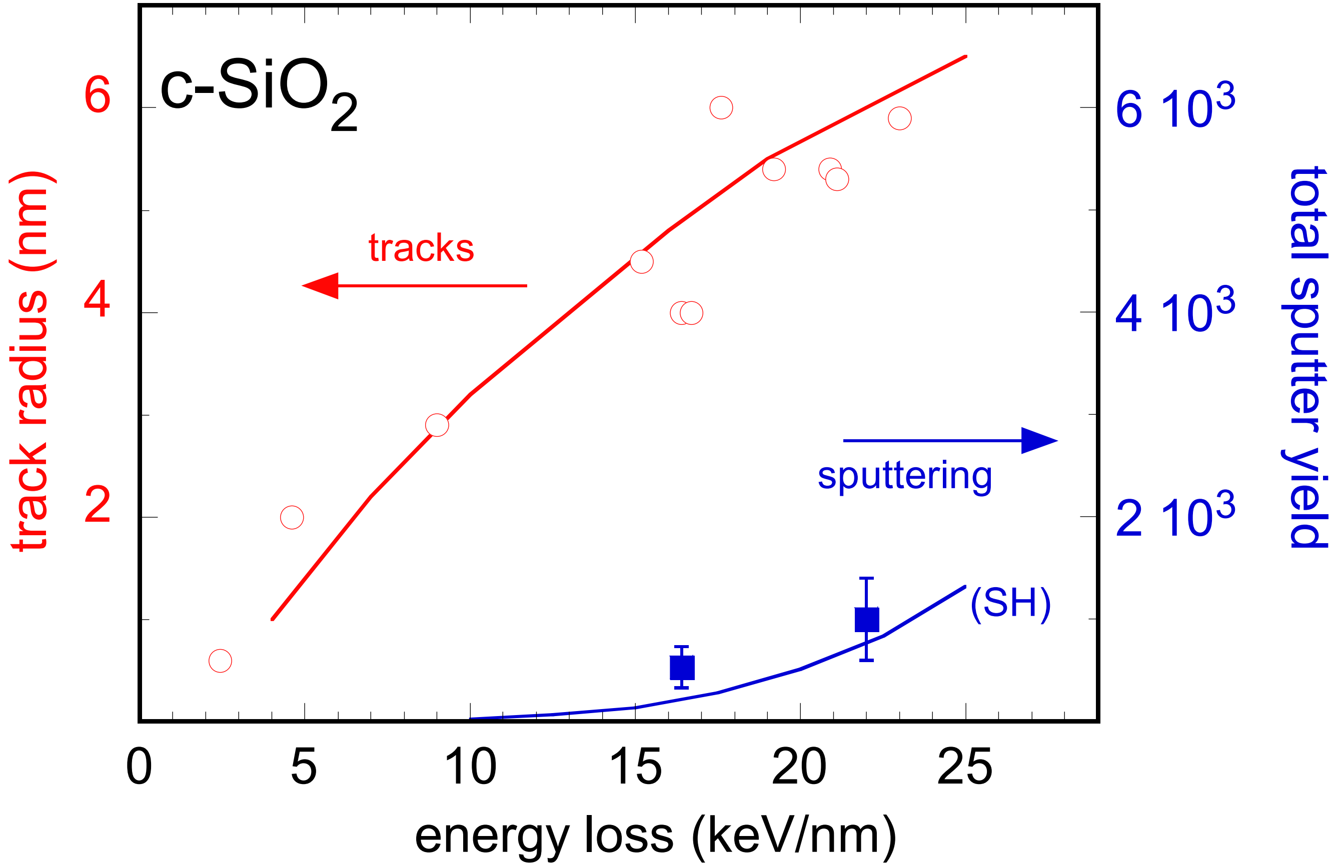
λ= 5 nm

Deposited energy density

MeV/u	15	1	0.07
α_R (nm)	6	2	0.6

SiO_2 Quartz

Calculation made at 1 MeV/u λ=3.8 nm



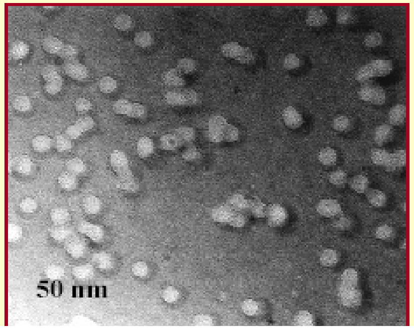
Toulemonde, Assmann, Grüner, Trautmann Phys. Rev. Lett. 88(2002)057602

Amorphous materials

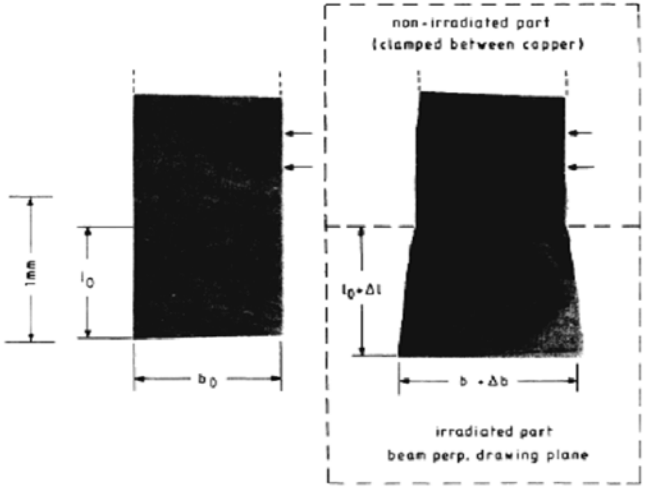
Amorphous metallic alloys

1983. Anisotropic growth of amorphous metallic alloys after incubation fluence

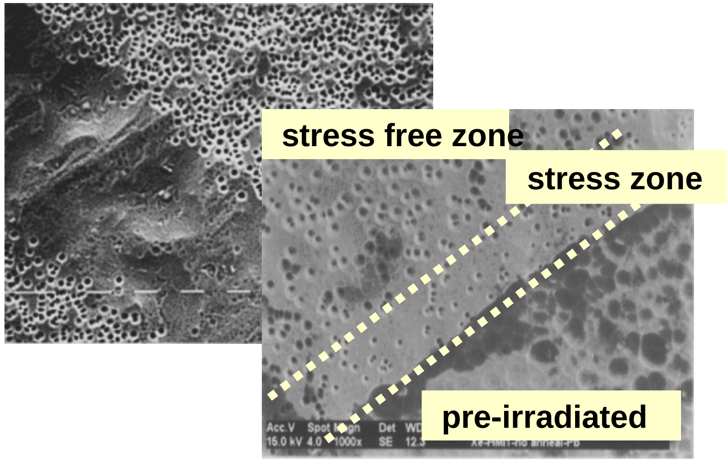
Amorphous Ni_3B



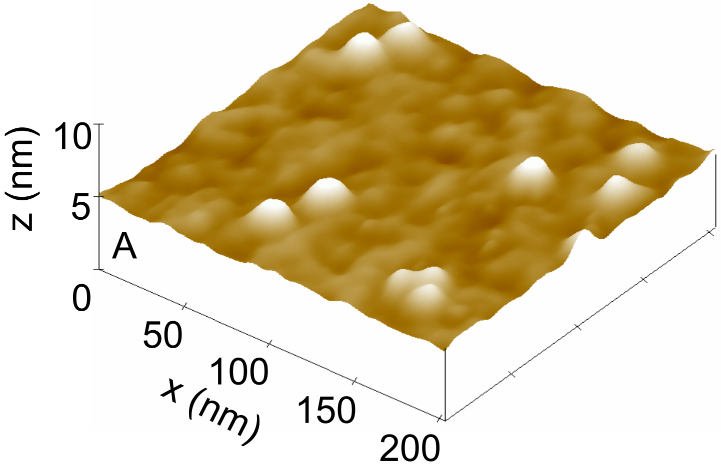
Dunlop et al. Nucl. Instr. Meth. B146(1998)222



S. Klaumünzer and G. Schumacher PRL 51(1983)1987



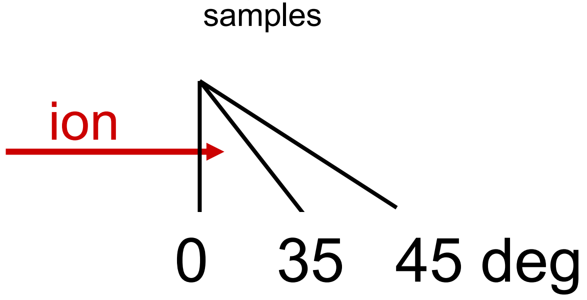
Trautmann et al. Rad. Eff. Def. Sol. 126(1993)207
Phys Rev. Lett. 85(2000)3648

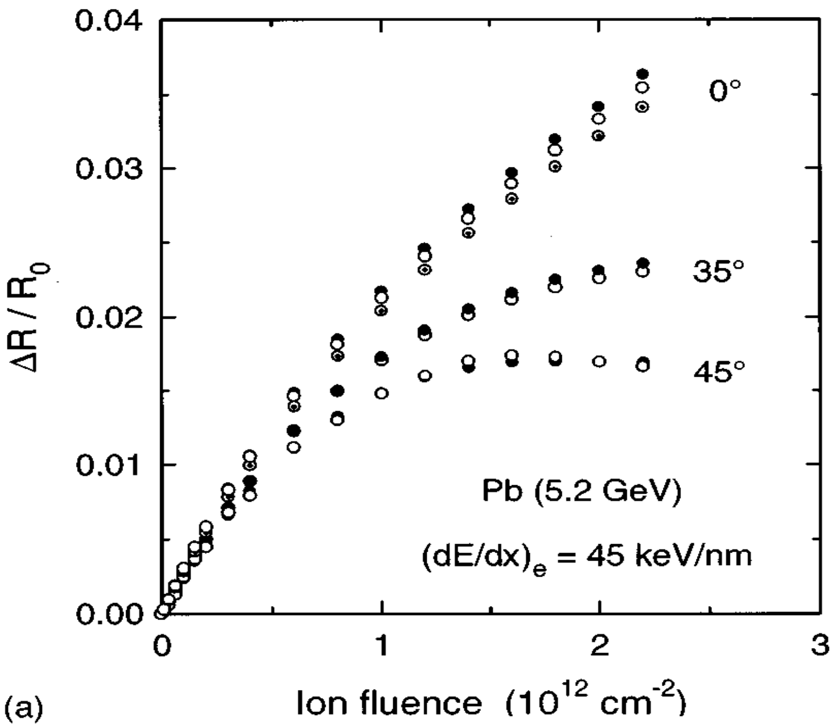


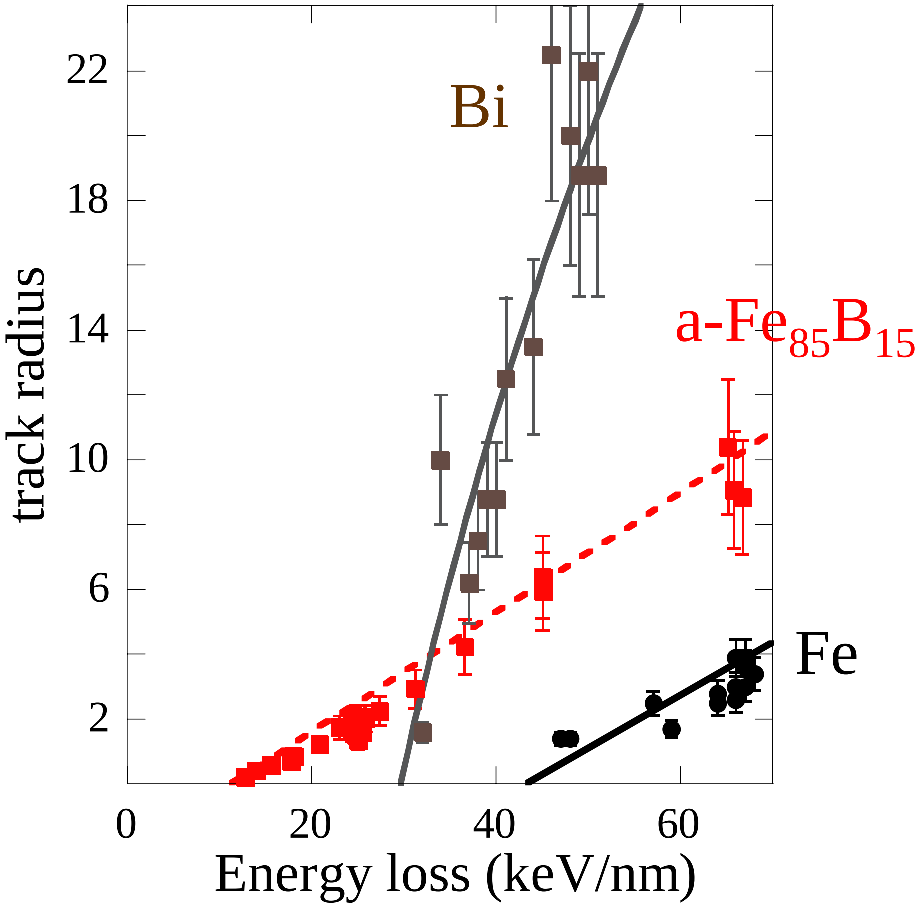
Audouard et al.
Europhys. Lett. 40(1997)527

Amorphous metallic alloys

1983. Anisotropic growth of amorphous metallic alloys after incubation fluence

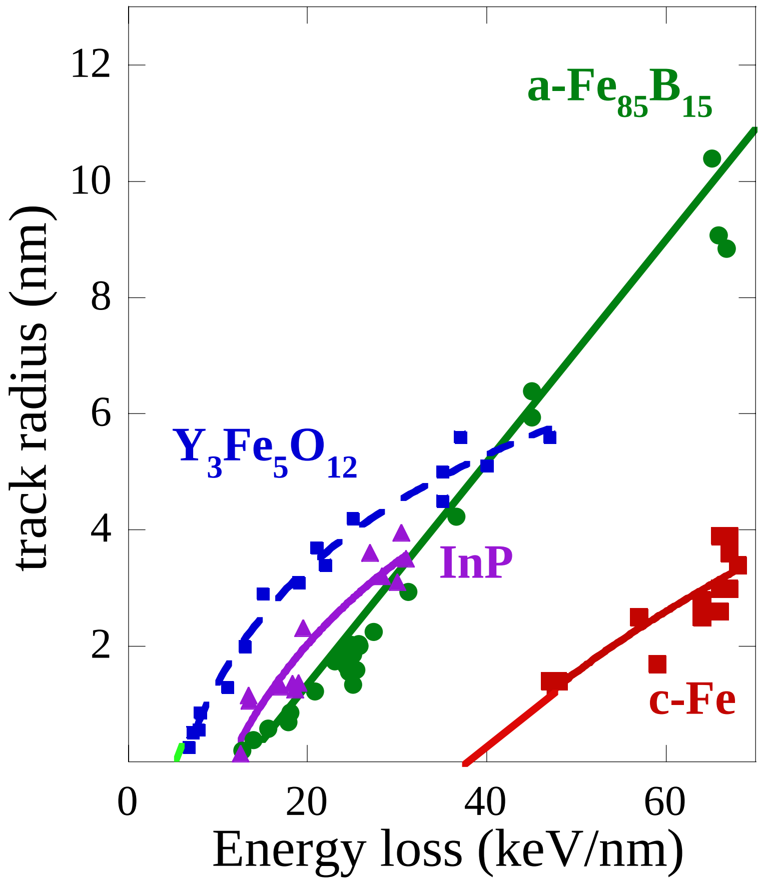






A. Audouard et al. Europhys. Lett. 3(1983)331

Track formation in bulk



insulators

YES polymers, ionic crystals, oxydes (**SiO_2**), etc…

---

semiconductors

YES GeS, InP, $Si_{0.5}Ge_{0.5}$

NO Si >26[?], Ge >30

keV/nm

---

metals

YES Fe, **Bi**, Ti, Co, Zr

NO Cu, Ag, Pt, **Ni**, Nb

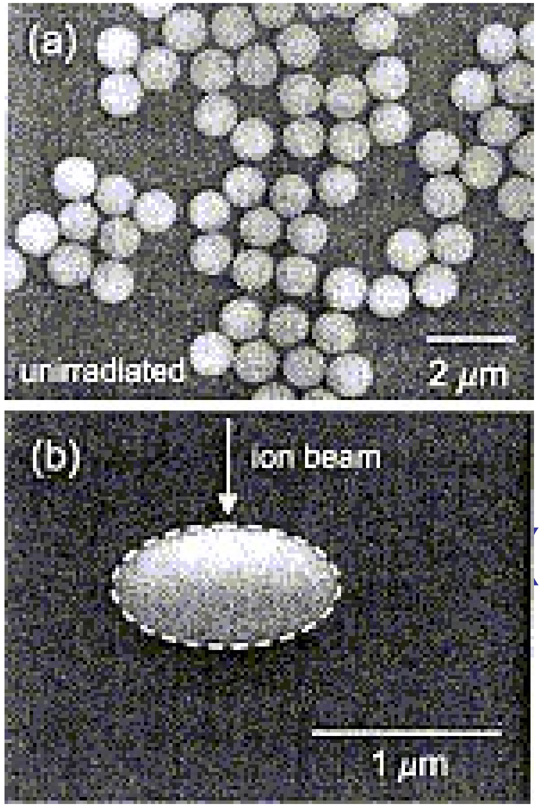
YES **all amorphous alloys**

$Y_3Fe_5O_{12}$	**Meftah et al. Phys. Rev. B48(1993)920**
InP	**Wesch et al. Nucl. Instr. Meth. B257(2007)283**
c-Fe	**Dunlop et al. Nucl. Instr. Meth. B90(1994)33**
a-$Fe_{85}B_{15}$	**Audouard et al. J. Phys. Cond. Mat. 5(1993)995**

Vitreous SiO_2

Anisotropic growth

a-SiO$_2$ – balls



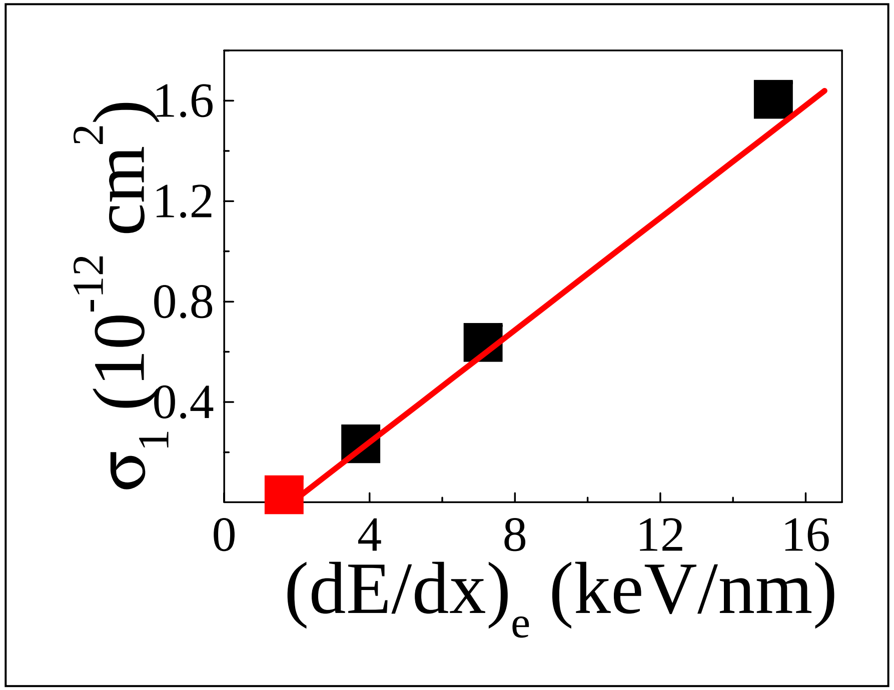
Threshold :

0.6 keV/nm

(at 0.025 MeV/u)

T van Dillen et al., Nucl. Instr. Meth. B 175-177 (2001) 350

a-SiO$_2$ bulk

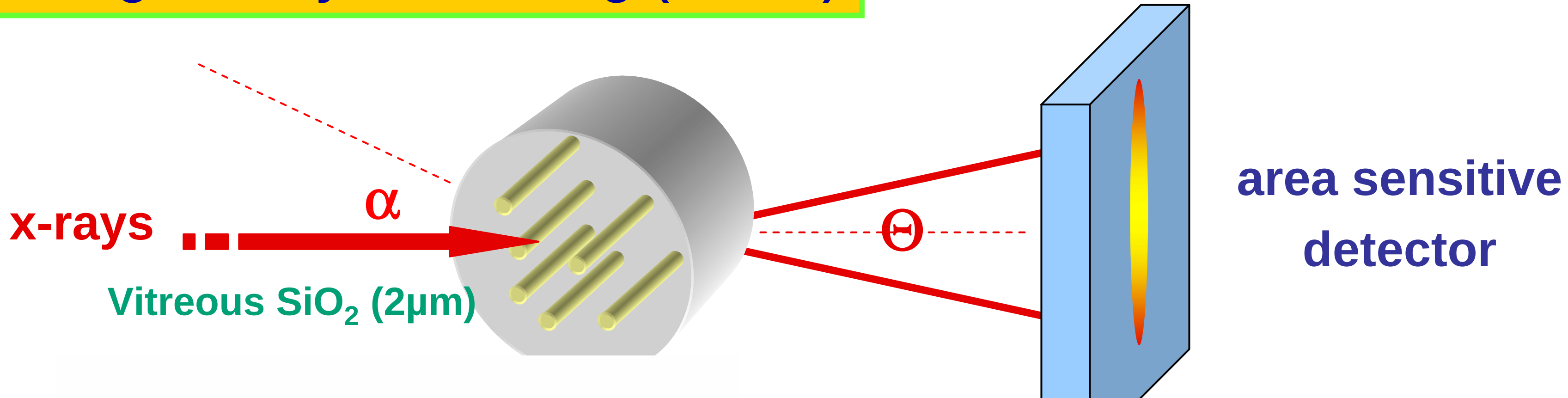


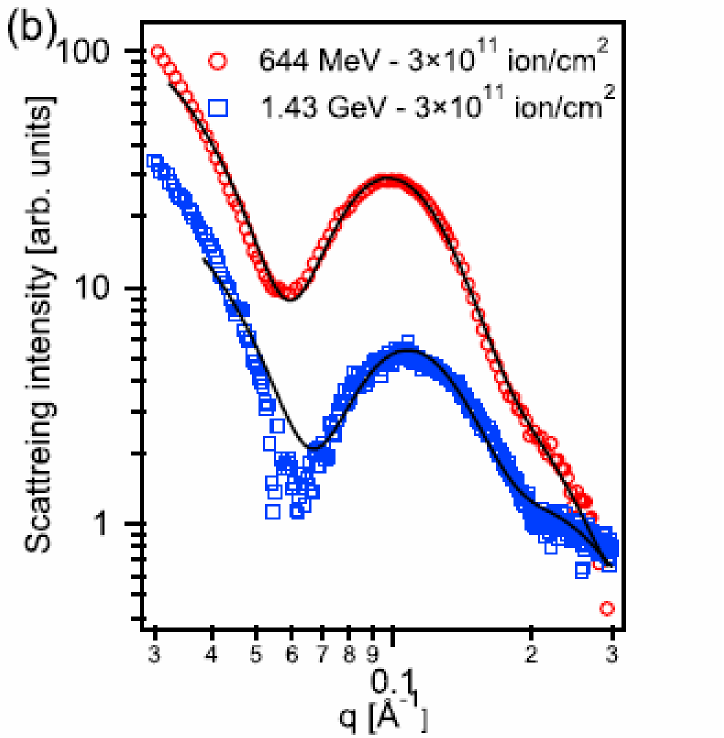
Threshold : 2 keV/nm

(3 MeV/u)

A. Benyagoub et al. Nucl. Instr. Meth. B 65 (1992) 228

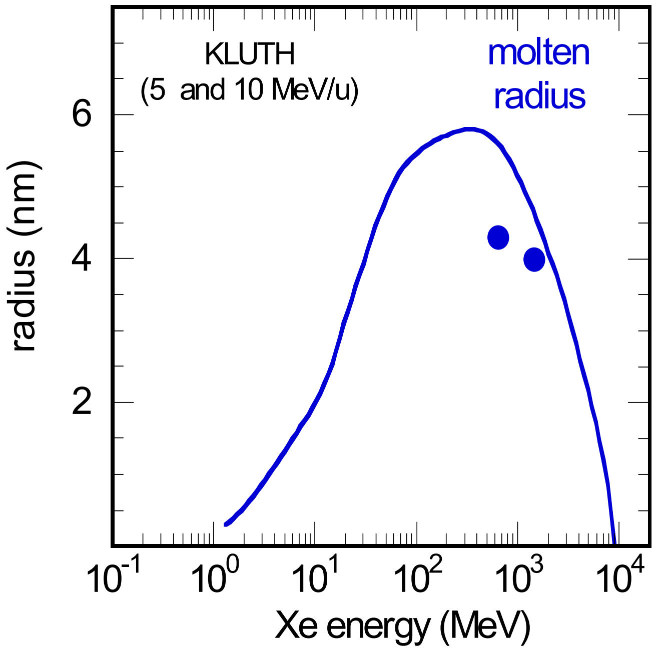
Small-angle x-ray scattering (SAXS)

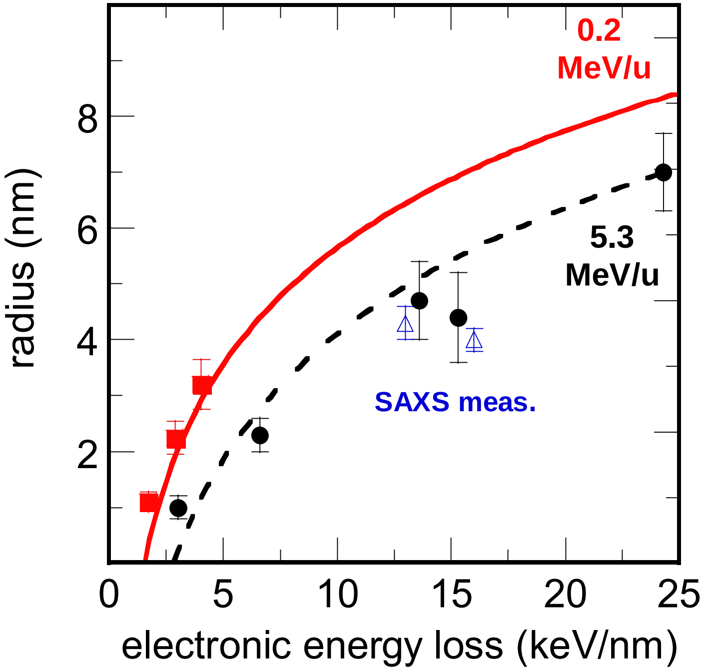




Kluth et al. Phys Rev. Lett. 101 (2008)175503

SiO_2 amorphous λ=3 nm

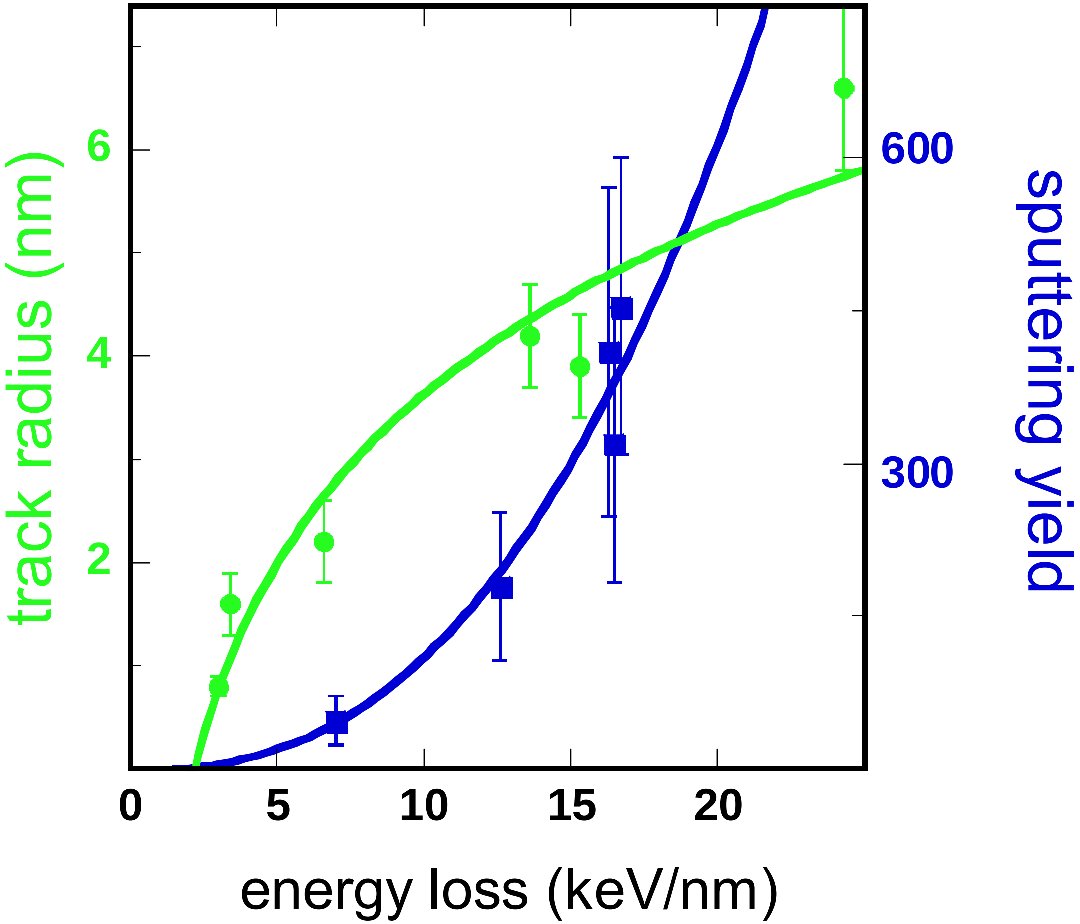




Rotaru et al. To be published in NIMB

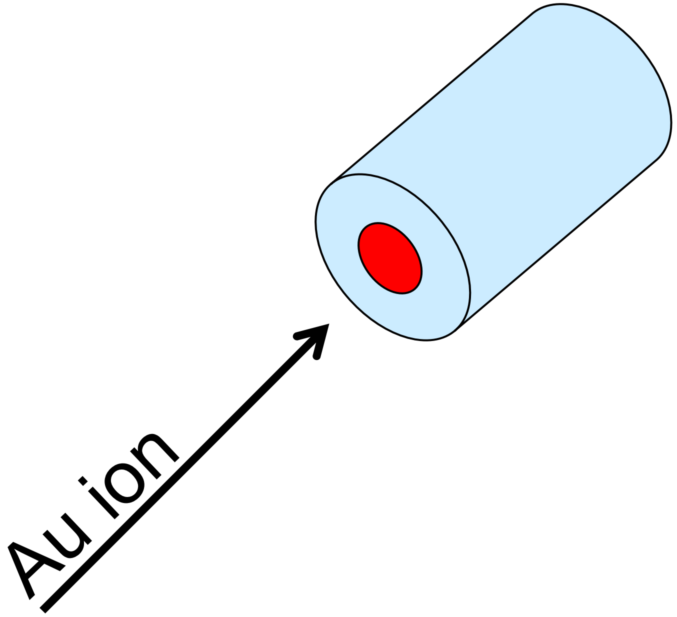
Kluth et al. Phys Rev. Lett. 101 (2008)175503

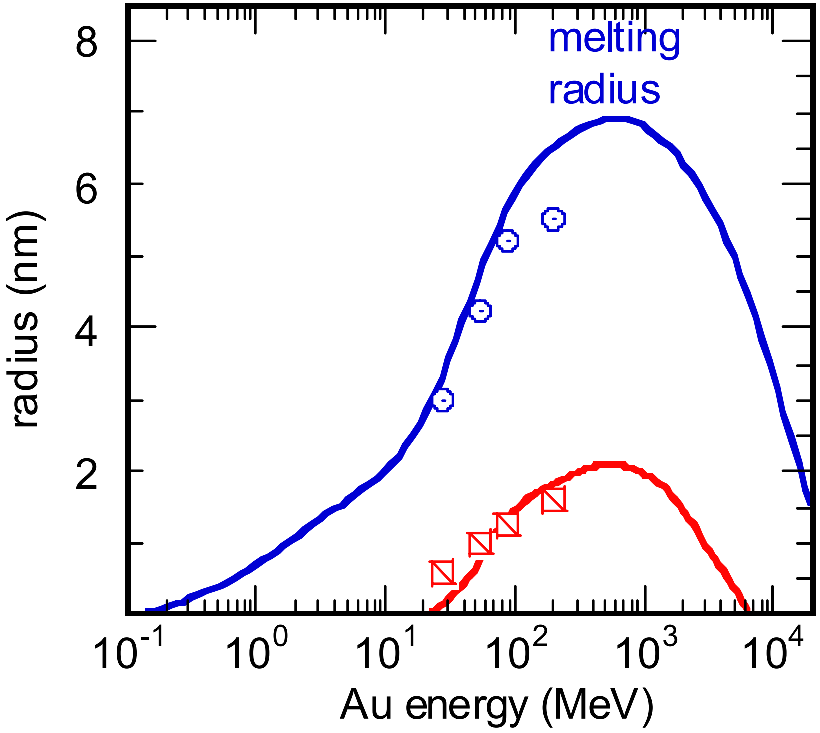
SiO_2 amorphous λ=3 nm



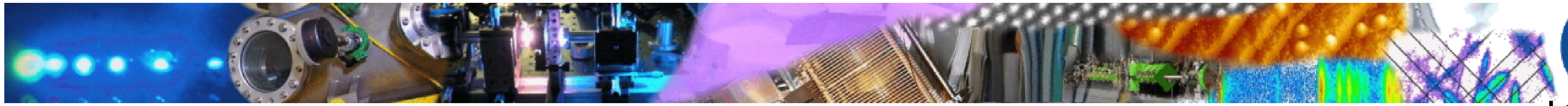
Tracks: Rotaru to be published in NIMB al.
Sputtering: Assmann, Toulemonde,Trautmann unpublished data

SiO_2 amorphous λ=3 nm





Kluth et al. Phys Rev. Lett. 101 (2008)175503



Complex Oxides at Extreme Conditions

►BASIC SCIENCE: Solid at Extreme Conditions

• complex phase diagram• unique disordering mechanism

effect of irradiation, pressure, and temperature?

►NUCLEAR ENGINEERING: Structural Modifications

• energy-relevant materials • enhanced radiation stability

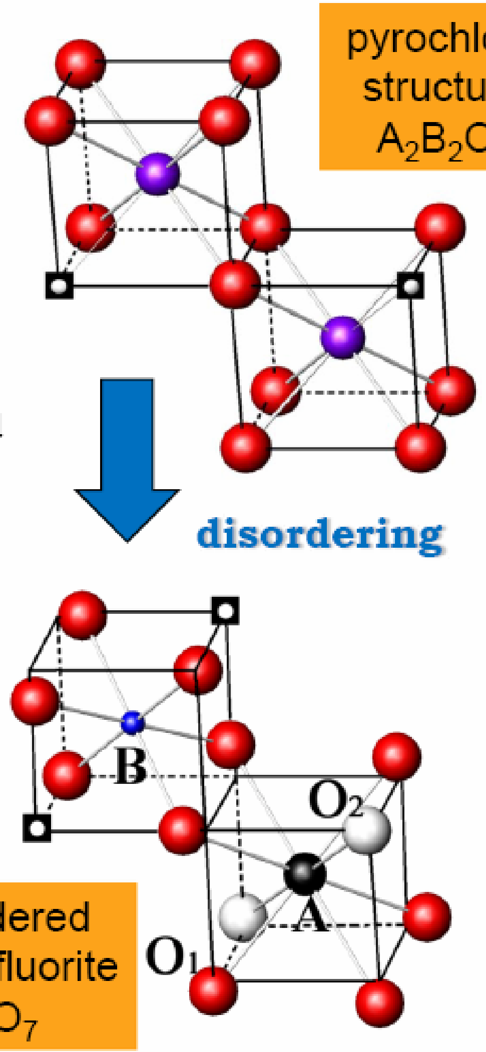
internal structure of swift heavy ion tracks?

►APPLICATION: Nanoscale Phase Transitions

• flexibility in structure and composition • numerous industrial applications

novel materials with unique properties?

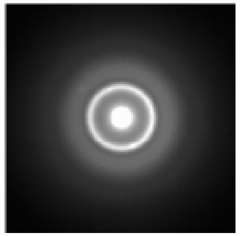
Ion-Induced Modifications in Pyrochlore



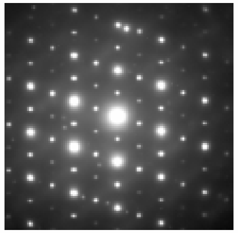
pyrochlore structure $A_2B_2O_7$

disordered defect-fluorite A_4O_7

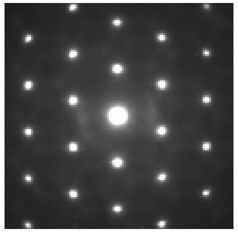
M.A. Subramanian, G. Aravamudan and G.V.S. Rao, *J. Solid State Chem.* (1983).



amorphous



pyrochlore



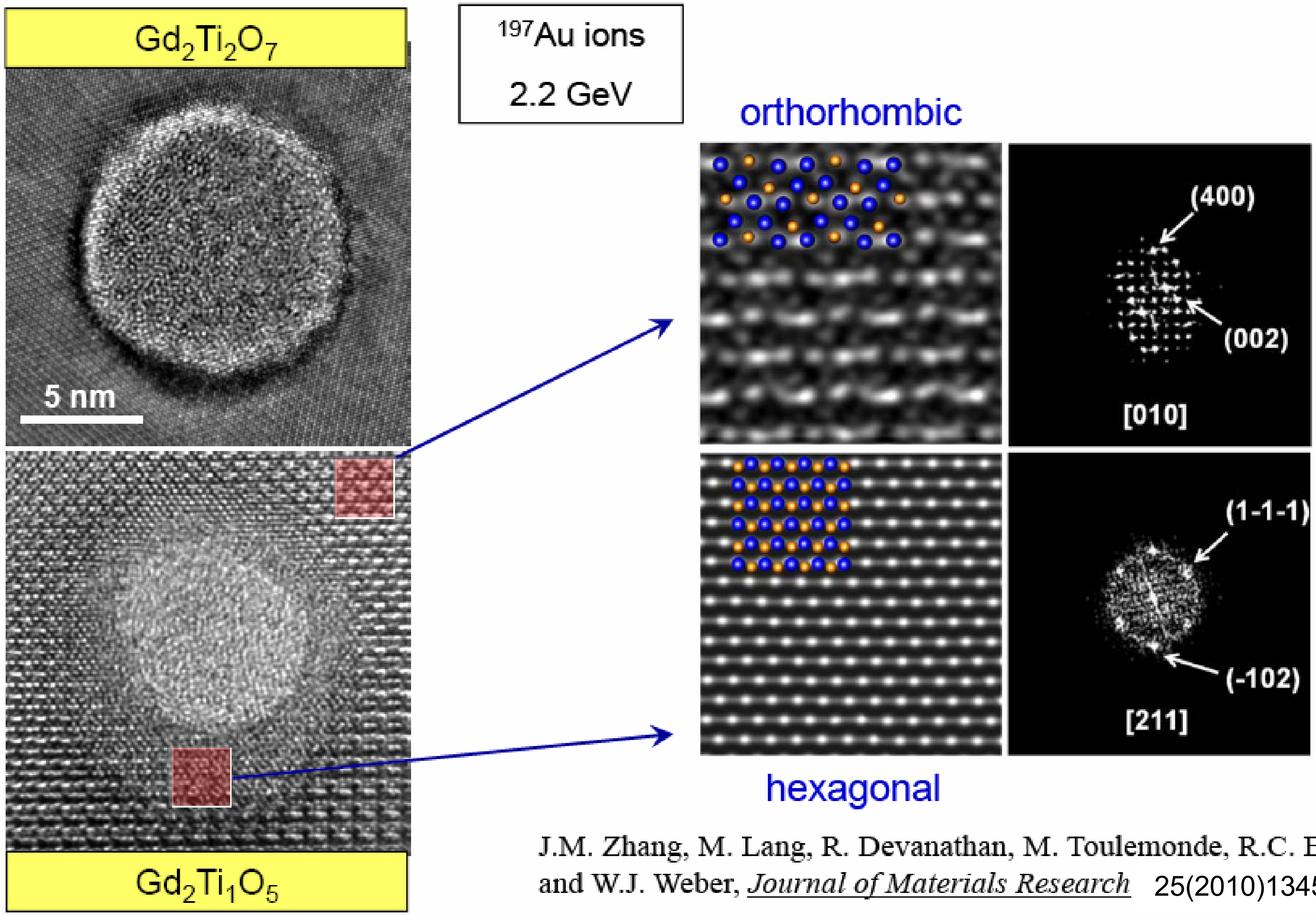
defect fluorite

cation radius ratio r_A/r_B

S.X. Wang *et al.*, J. Mater. Res. (1999).
B.D. Begg *et al.*, J. Nucl. Mater. (2001).

J. Lian *et al.*, Phys. Rev. Lett. (2001).

Effect of Material Composition



$Gd_2Ti_2O_7$

^{197}Au ions

2.2 GeV

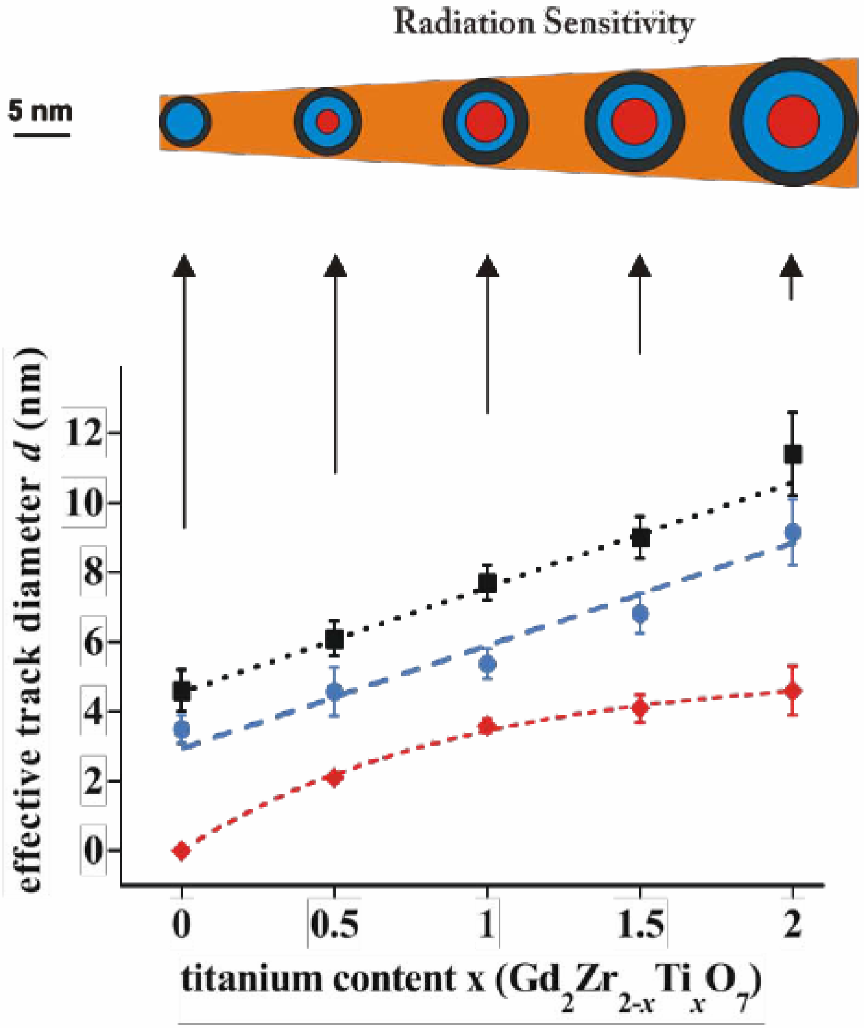
orthorhombic

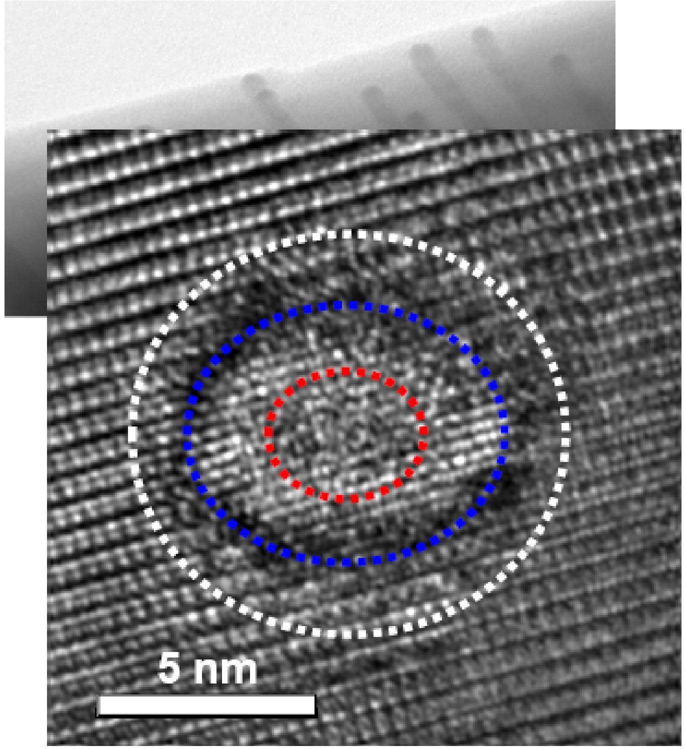
hexagonal

$Gd_2Ti_1O_5$

J.M. Zhang, M. Lang, R. Devanathan, M. Toulemonde, R.C. Ewing, and W.J. Weber, *Journal of Materials Research* 25(2010)1345

Single Ion Tracks: Damage Morphology



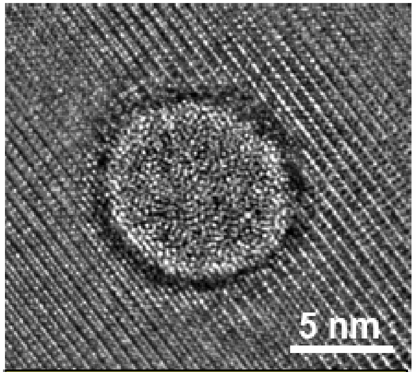


$Gd_2Ti_2O_7$

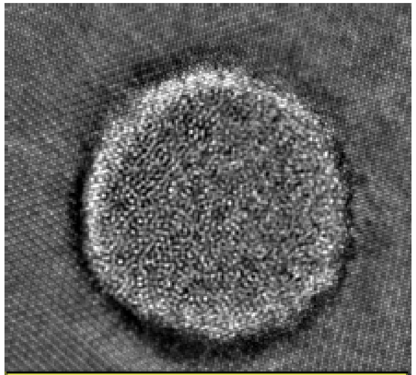
M. Lang, J. Lian, J. Zhang, F.X. Zhang, W.J. Weber, C. Trautmann, and R.C. Ewing, *Phys.Rev. B* (2009).

Effect of Irradiation Temperature

8 K 300 K 1000 K



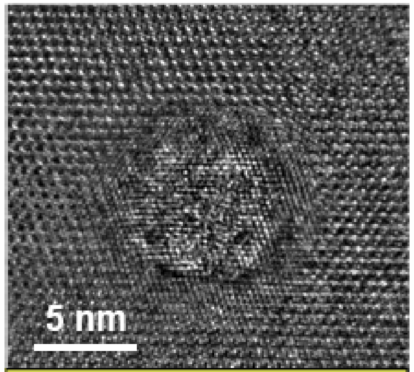
$Gd_2Ti_2O_7$ – ^{197}Au



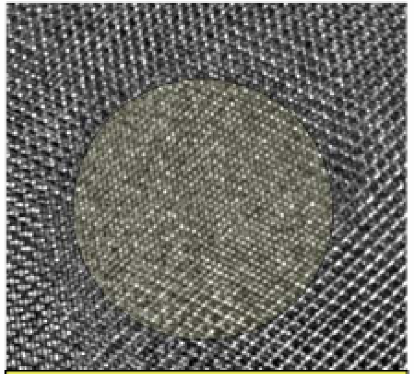
$Gd_2Ti_2O_7$ – ^{197}Au

epitaxial recrystallization

track-size decrease



Gd_2ZrTiO_7 – ^{197}Au



Gd_2ZrTiO_7 – ^{238}U

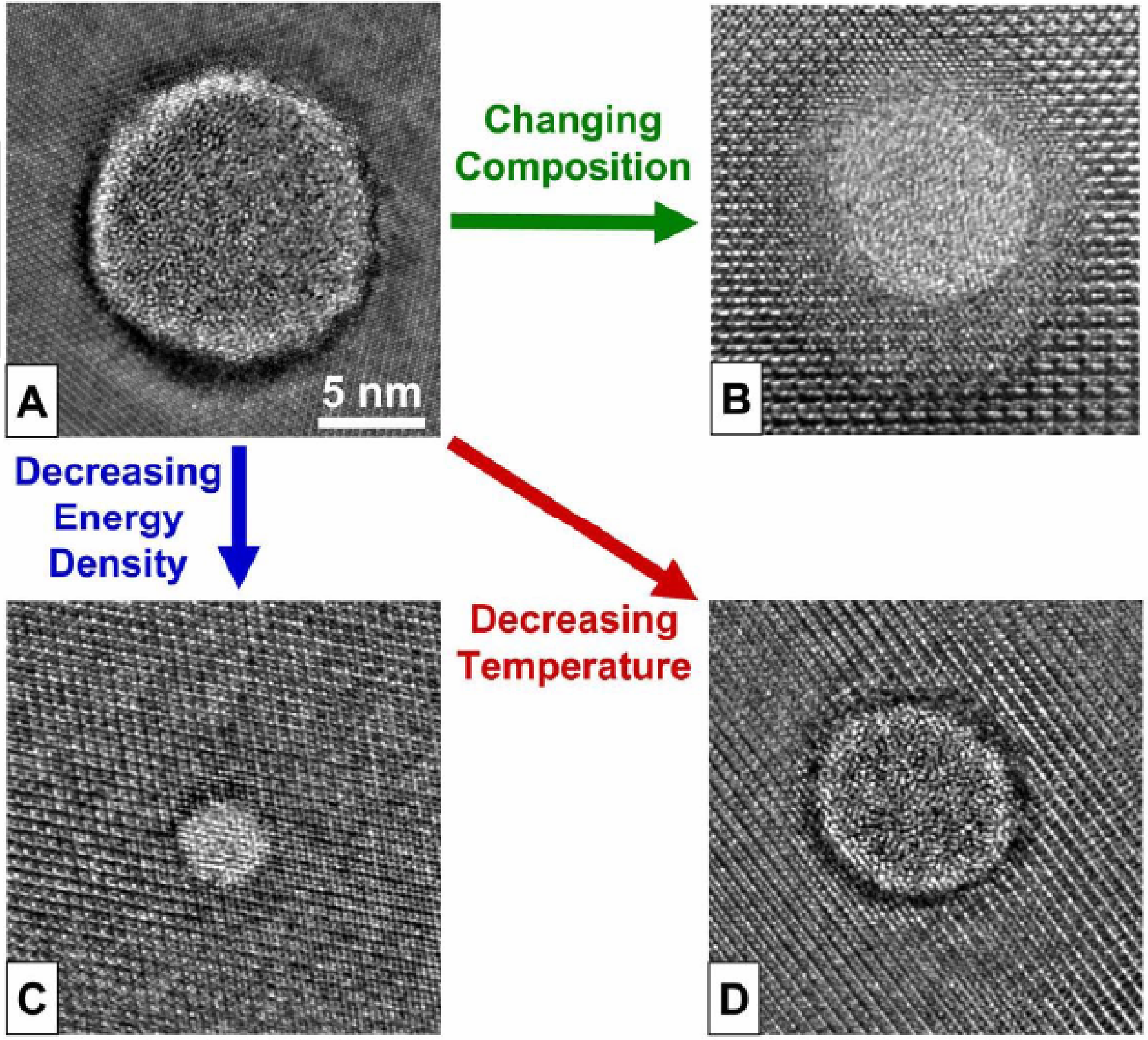
J.M. Zhang, M. Lang, M. Toulemonde, R.C. Ewing, and W.J. Weber, J. Mat. Reas. 25(2010)1345

Nanoscale Material Manipulation

$Gd_2Ti_2O_7$

2.2-GeV ^{197}Au

300 K



$Gd_2Ti_1O_5$

2.2-GeV ^{197}Au

J.M. Zhang, M. Lang, R. Devanathan, M. Toulemonde, R.C. Ewing, and W.J. Weber, *Journal of Materials Research* 25(2010)1345

$Gd_2Ti_2O_7$

1.1-GeV ^{101}Ru

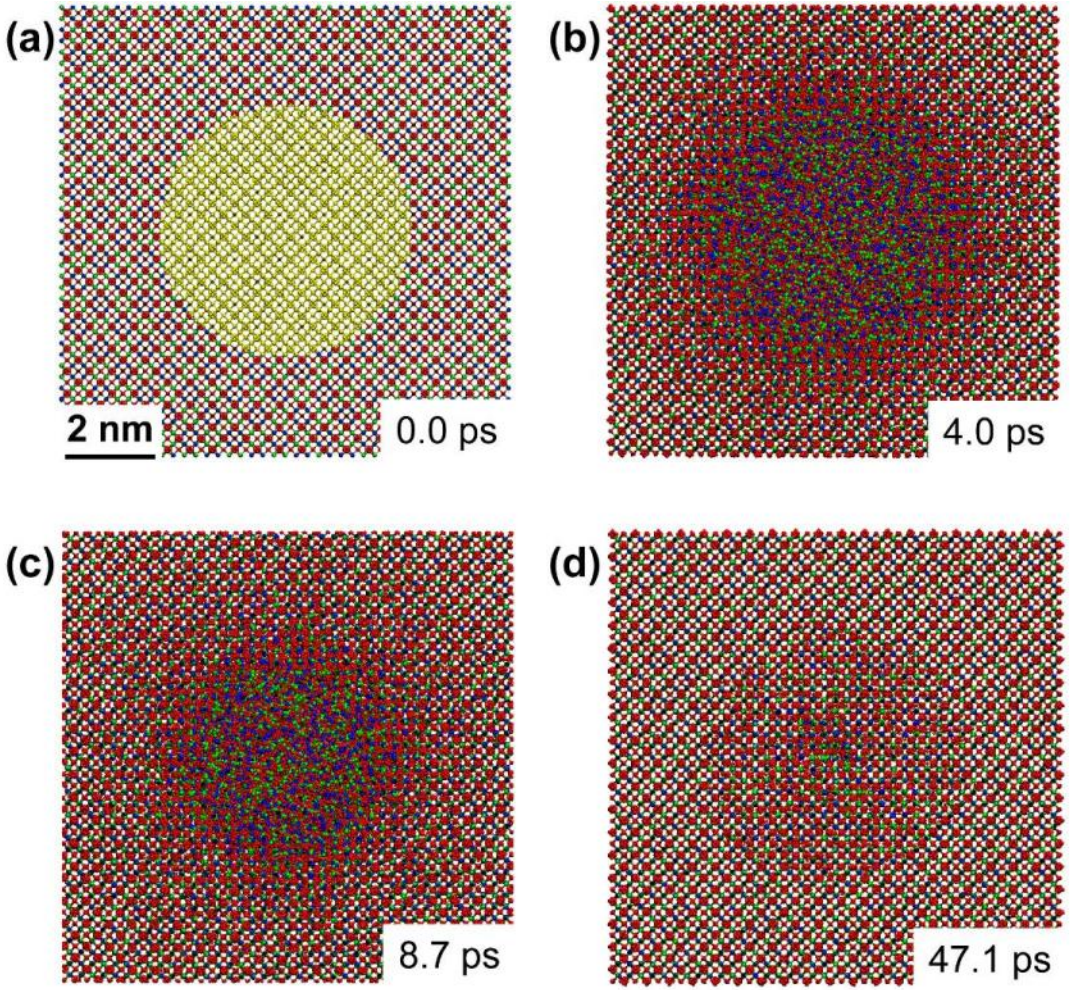
$Gd_2Ti_2O_7$

2.2-GeV ^{197}Au

8 K

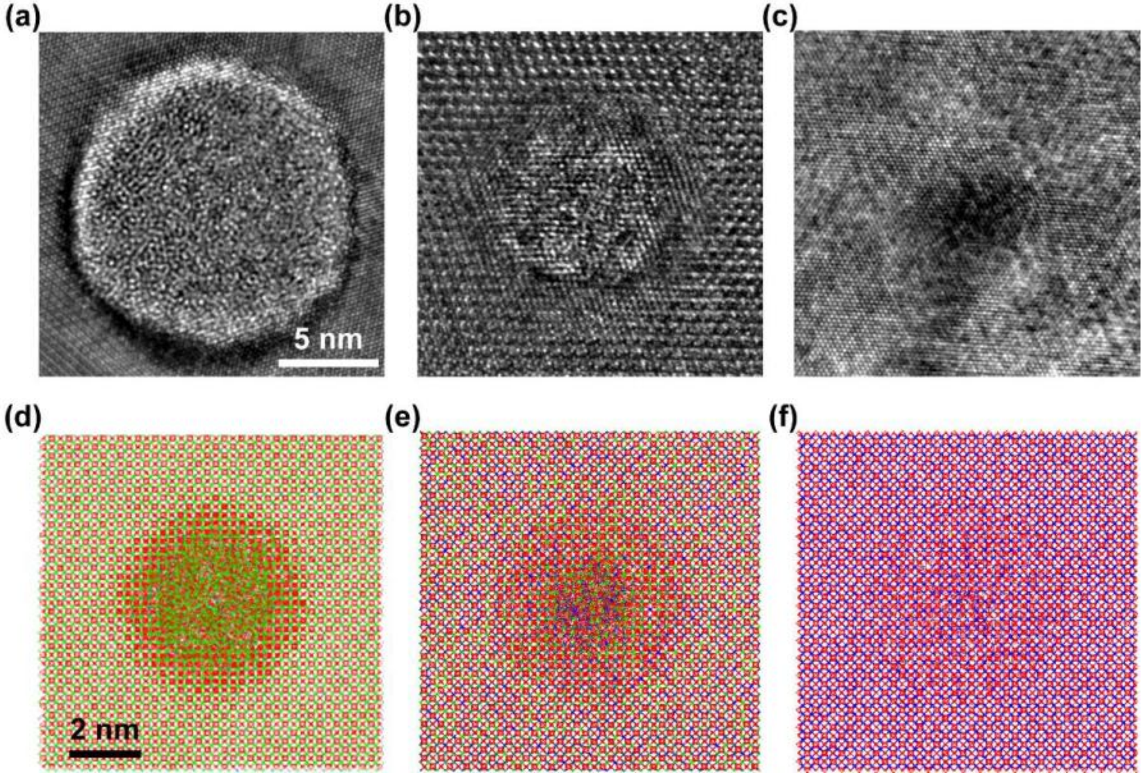
Comparison with MD calculations

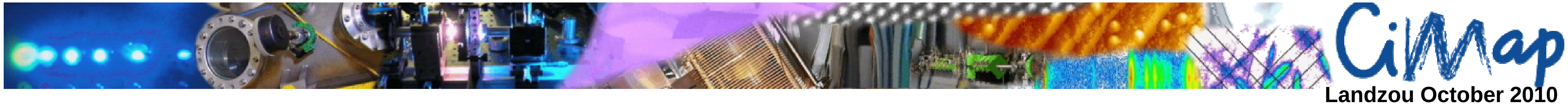
$Gd_2Zr_2O_7$



Comparison with MD calculations

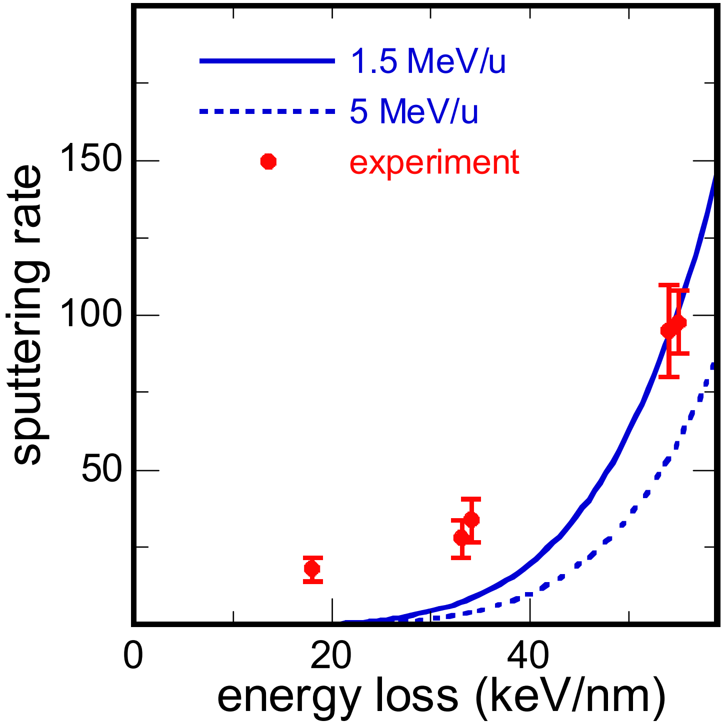
$Gd_2Ti_2O_7$ $Gd_2Ti_1Zr_1O_7$ $Gd_2Zr_2O_7$





Non amorphisable oxide crystal: UO$_2$

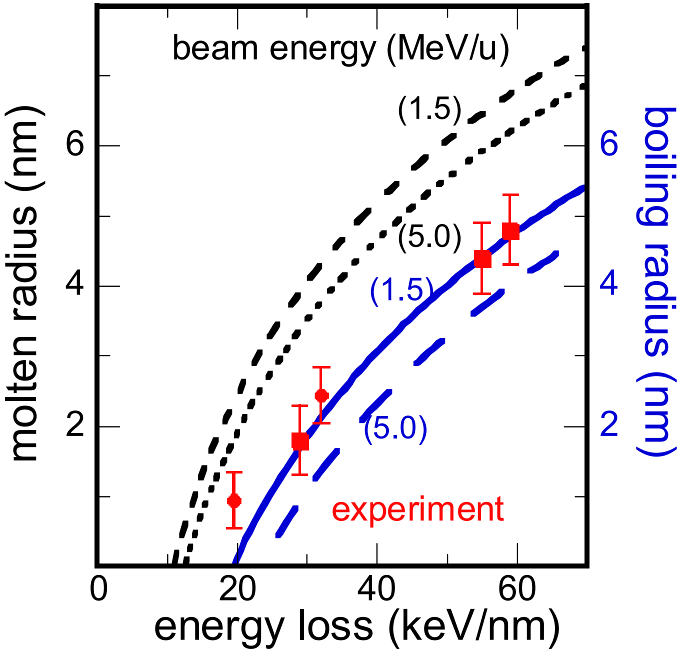
Sputtering



S. Schlutig PhD Thesis Caen (2001)

http://tel.archives-ouvertes.fr/tel-00002110/fr/

track



Wiss et al. NIMB 122 (1997) 583

Sonoda et al. NIMB 250 (2006) 114

Conclusions

Electron-phonon coupling λ seems to be the main parameter whatever is the material : insulators or metallic

- Defect annealing and defect creation in c-Fe
  - A criteria for track formation: overcomes the energy necessary to melt.
- Temperature effect in Bi
- Mixing at interface (Ni/Ti)
- Track and sputtering in c-SiO_2 associated to melt phase and vapor phase respectively

Energy distribution on electrons compared to λ velocity effect

Open questions:
- Some uncertainties on the g value for metallic materials….
- Meaning of λ for insulators ?
- Semi-conductors (Ni/Si)
- Transient thermal processes: validity in such short time?
- A second threshold of damage creation by vapor phase (a-SiO_2)?
- Non-amorphisable insulators??

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