Swift heavy ion induced damage in LiF: in (z < R) and beyond (z > R) the track

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NoRHDia, June 2008

- Why LiF?
- Track morphology in LiF crystals: dependence on dE/dx, E_{ion} ,Φ , T_{irr}
- Color centers beyond the track (z > R):

1) radiation sources; 2) distribution of color centers; 3)peculiarities for various ions

Open questions and outlook

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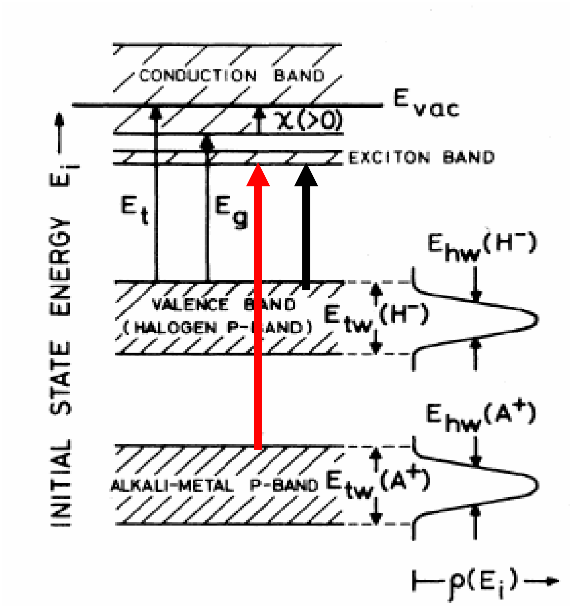
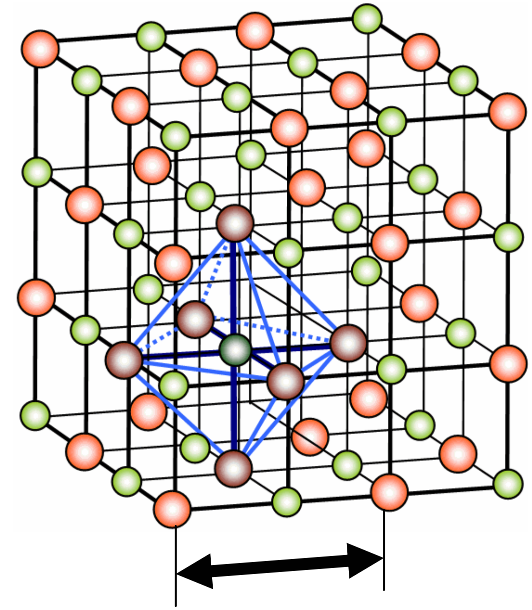


Li^{+} 2s

F^{-} $2p^{6}$

Li^{+} $1s^{2}$



a = 0.404 nm

LiF, cubic

E_g = 14.6 eV

E_{anion} = 13.6 eV

E_{cat} = 62 eV

Primary defect creation in dielectric materials

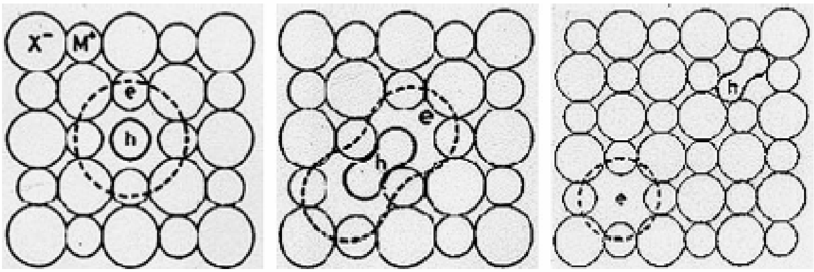
1. Atomic collisions

m m

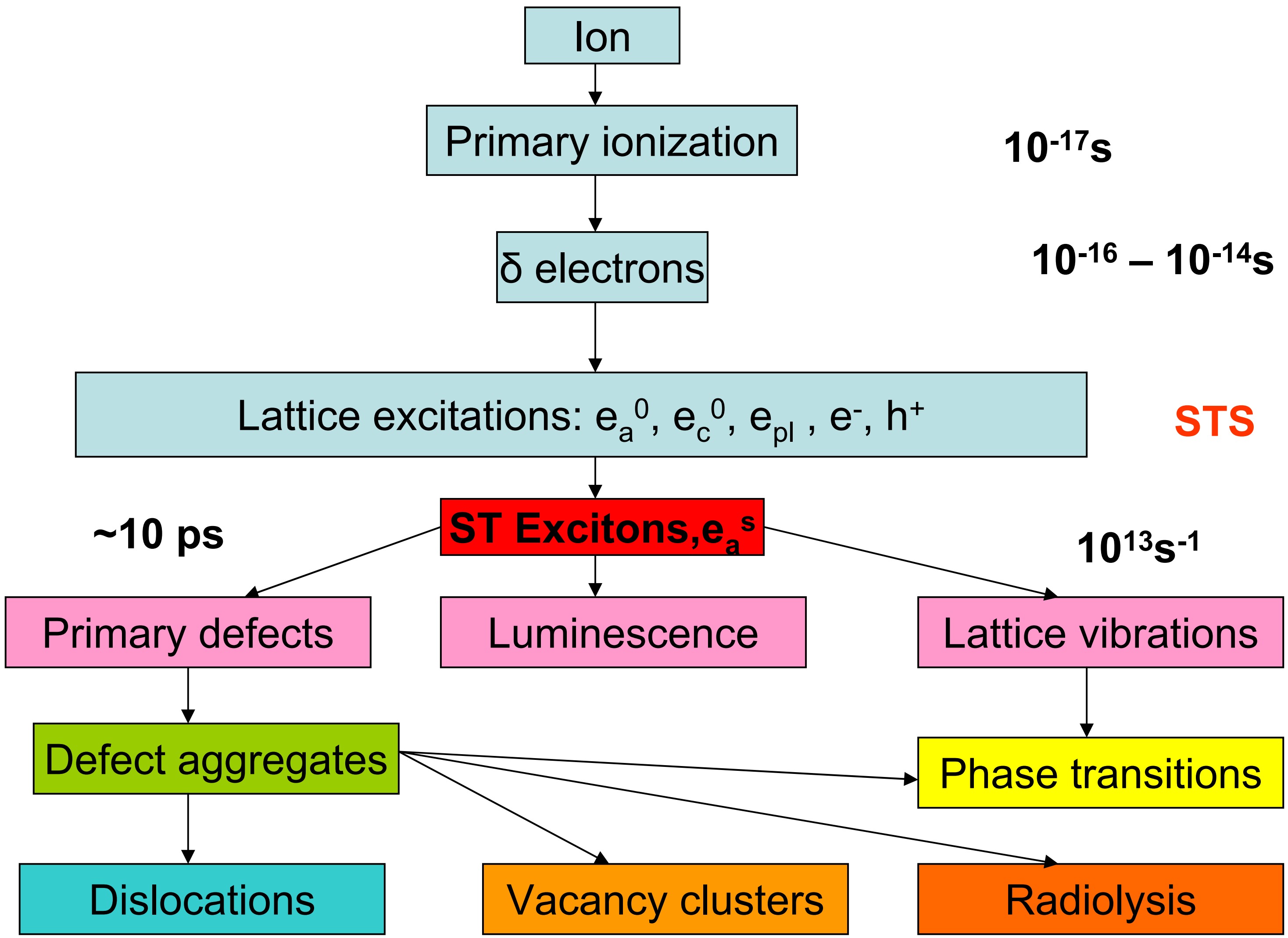
2. Decay of electronic
   excitations of the lattice

$$e^{o} \rightarrow e^{s}$$

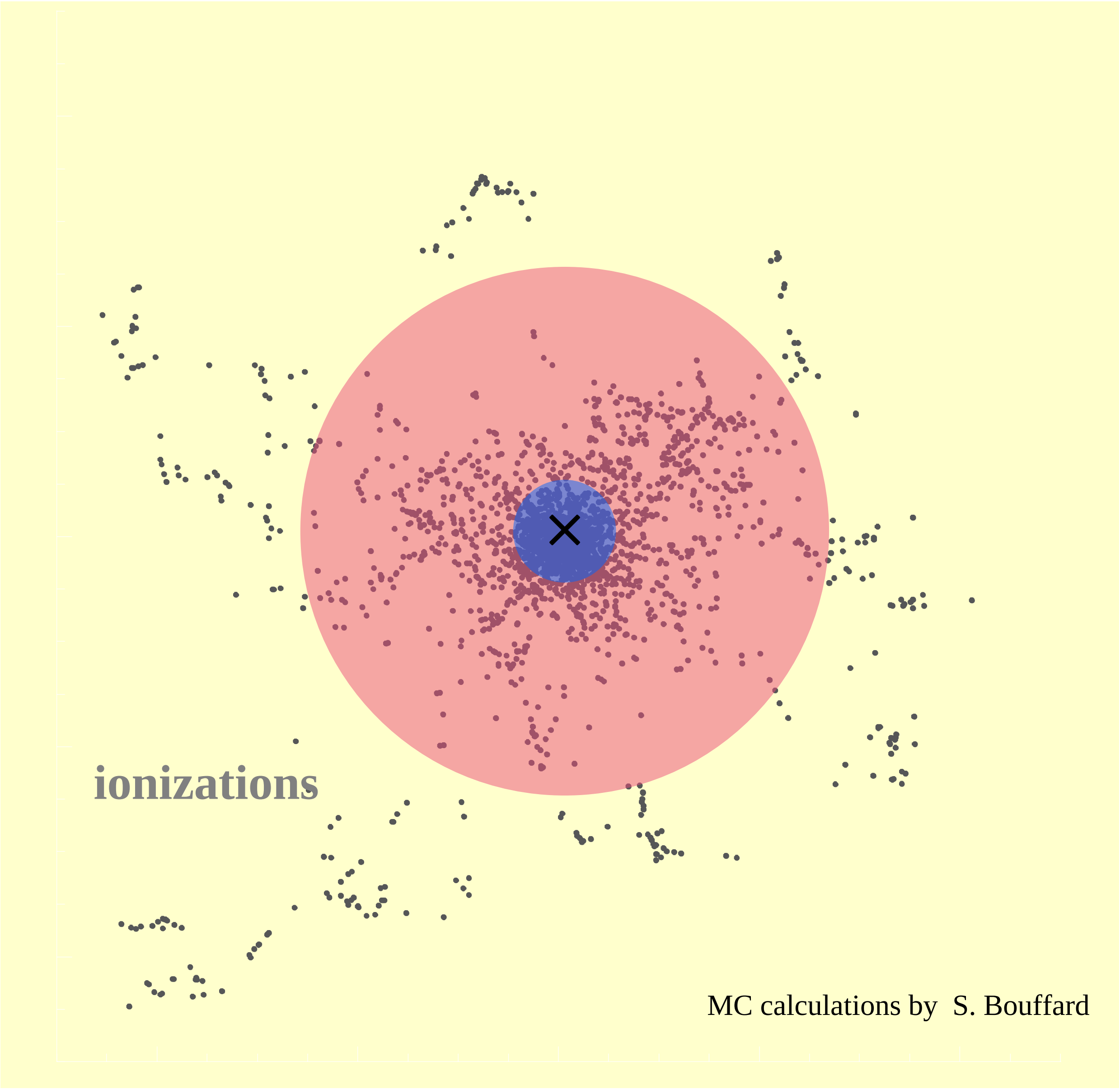
$$E^{s}_{ex} > E_{def}$$



Energy conversion and defect creation in ionic crystals by the exciton mechanism



Scheme of track morphology



	core
radius	1-2 nm
energy	~ 0.3 E_{tot}

	halo
radius	10-40 nm
energy	~ 0.7 E_{tot}

Track morphology in alkali halides:
Different damage via dE/dx

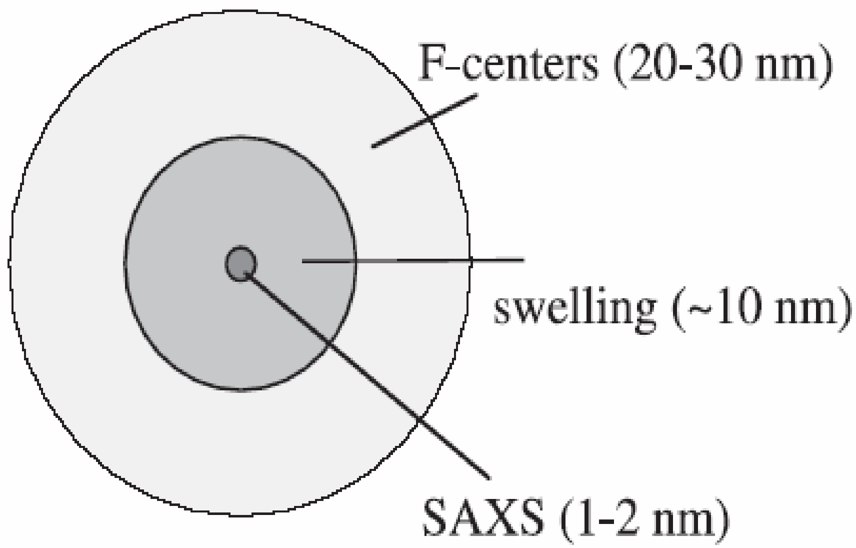
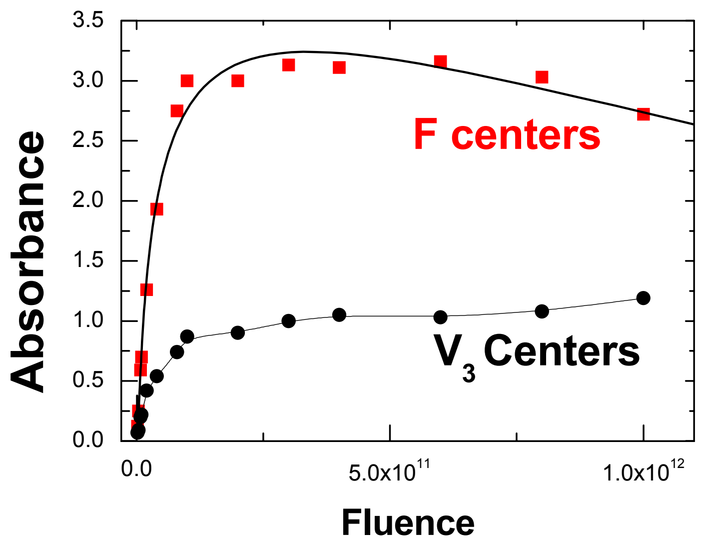


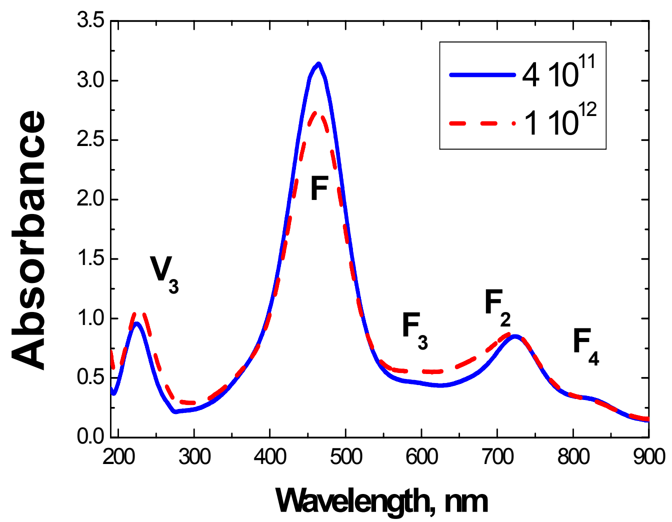
Fig. 14. The structure of tracks in LiF is described by (1) a large halo mainly consisting of single color centers, (2) a medium sized zone contributing to swelling, and (3) a small core region responsible for etching and SAXS.

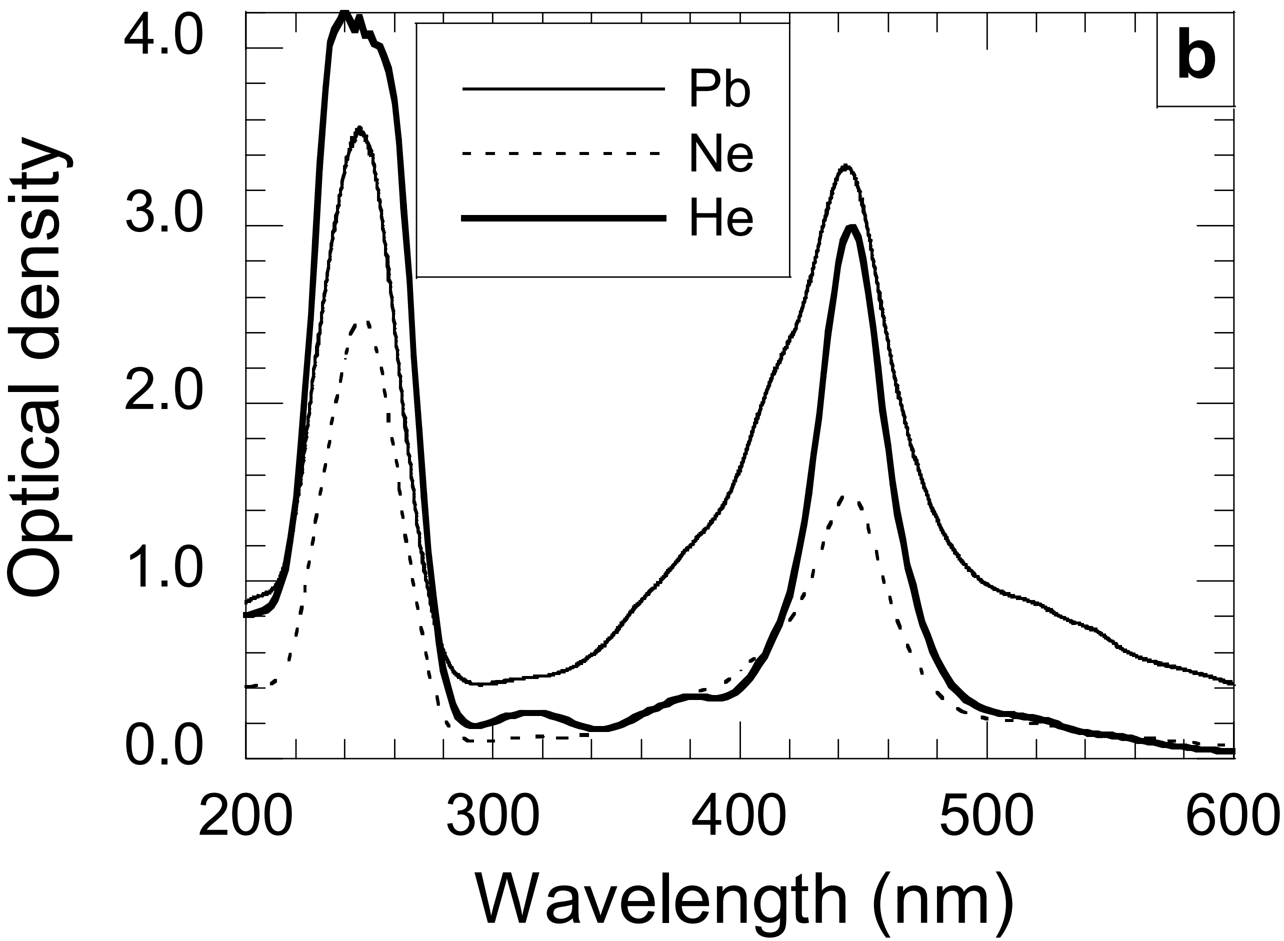
Au 2187 MeV induced aggregation in NaCl at 300 K

N_F decreases $F \rightarrow F_n$



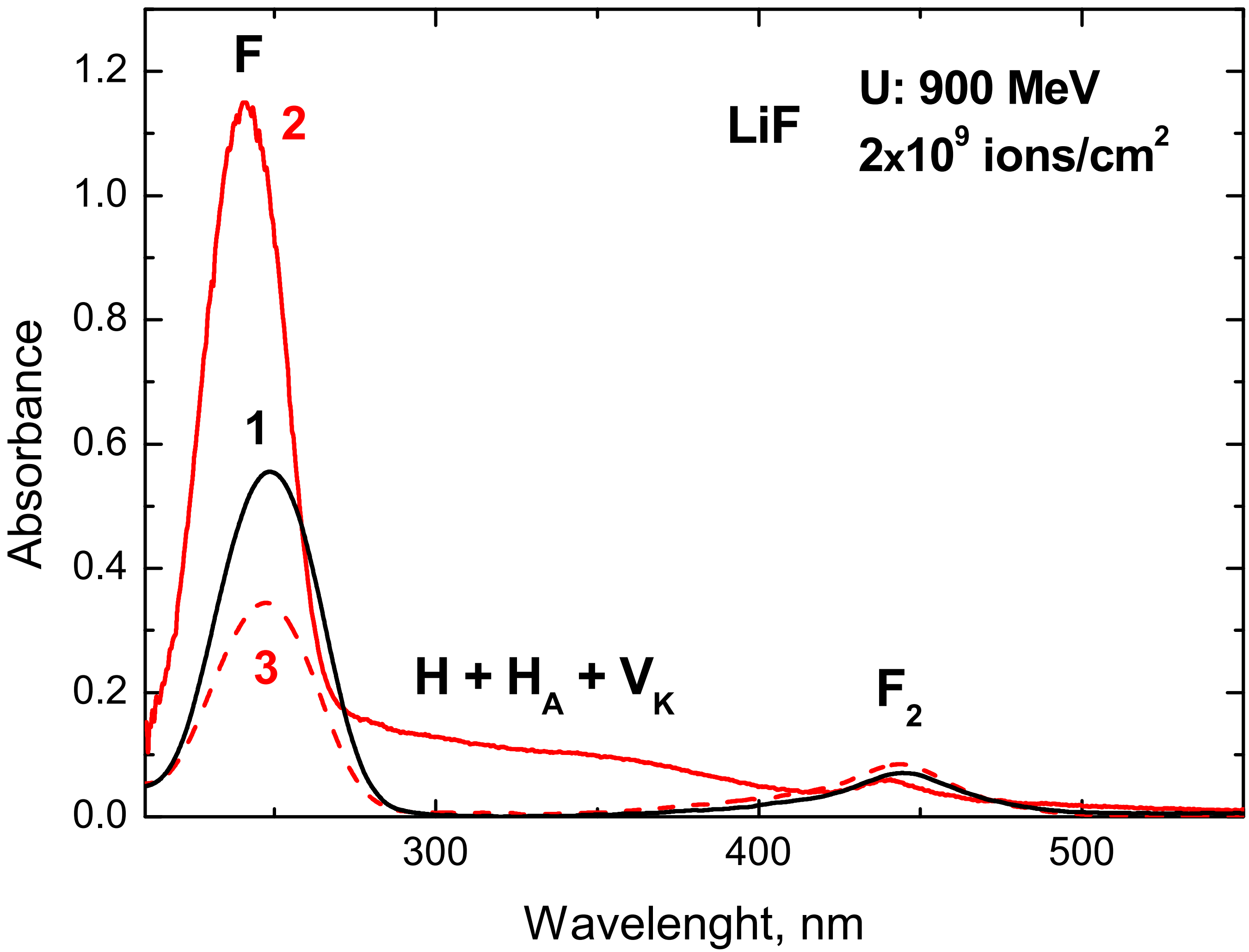
N_{V3} further increase



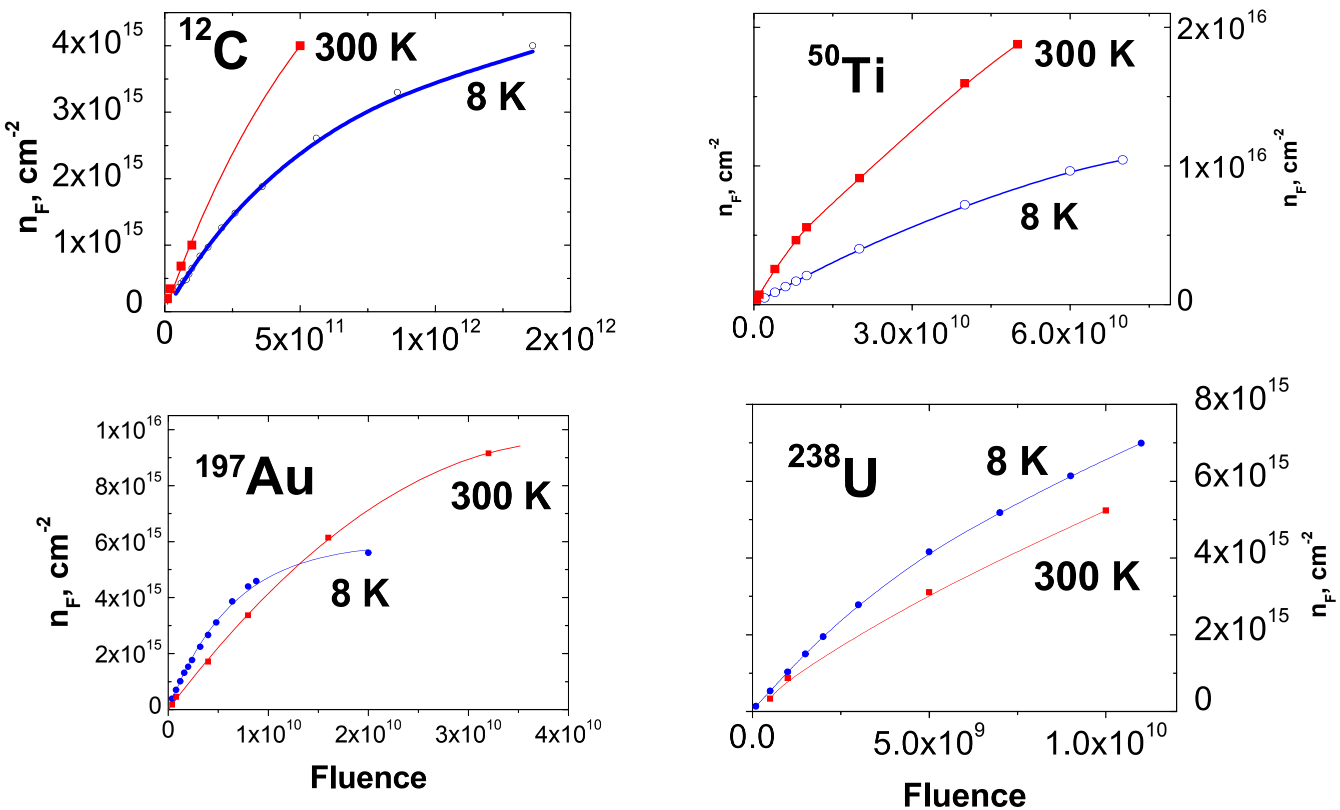


He 5 MeV, 10^{14}; **Ne** 31 Mev, 10^{13}; **Pb** 830 MeV, $1.2x10^{12}$

1 - n_F(300 K) =5.5x10^{15}cm^{-2} 2 - n_F(8 K) =7x10^{15}cm^{-2}
3 - n_F(300 K) =3.3x10^{15}cm^{-2} after 8 K



Efficiency of color center creation at 8 and 300 K



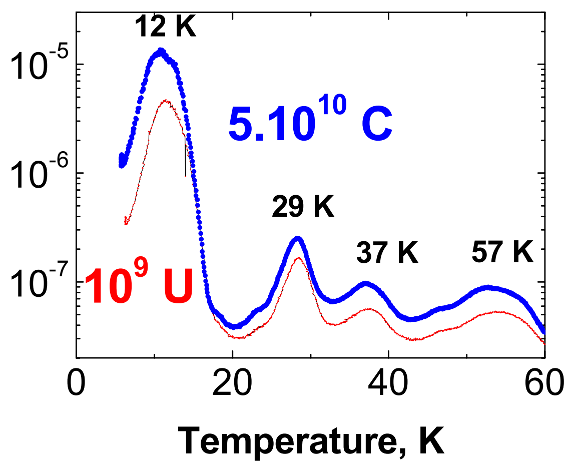
TSL in LiF and NaCl Crystals at 8 K

Defects with low thermal stability – low local heating in the track

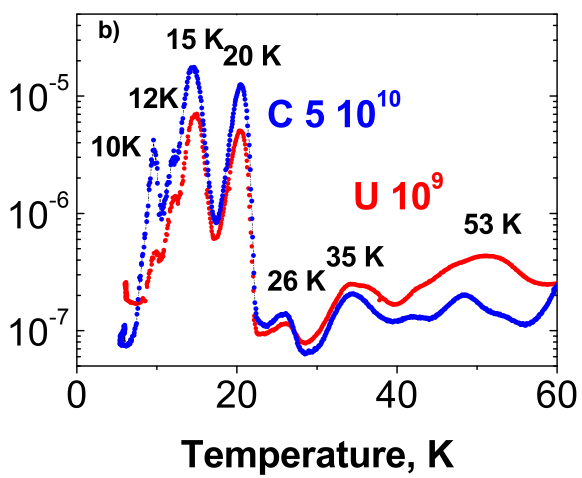
No dependence on dE/dx

10 – 25 K I centers (Lushchik et al. [3]) 25 – 60 K H centers

LiF

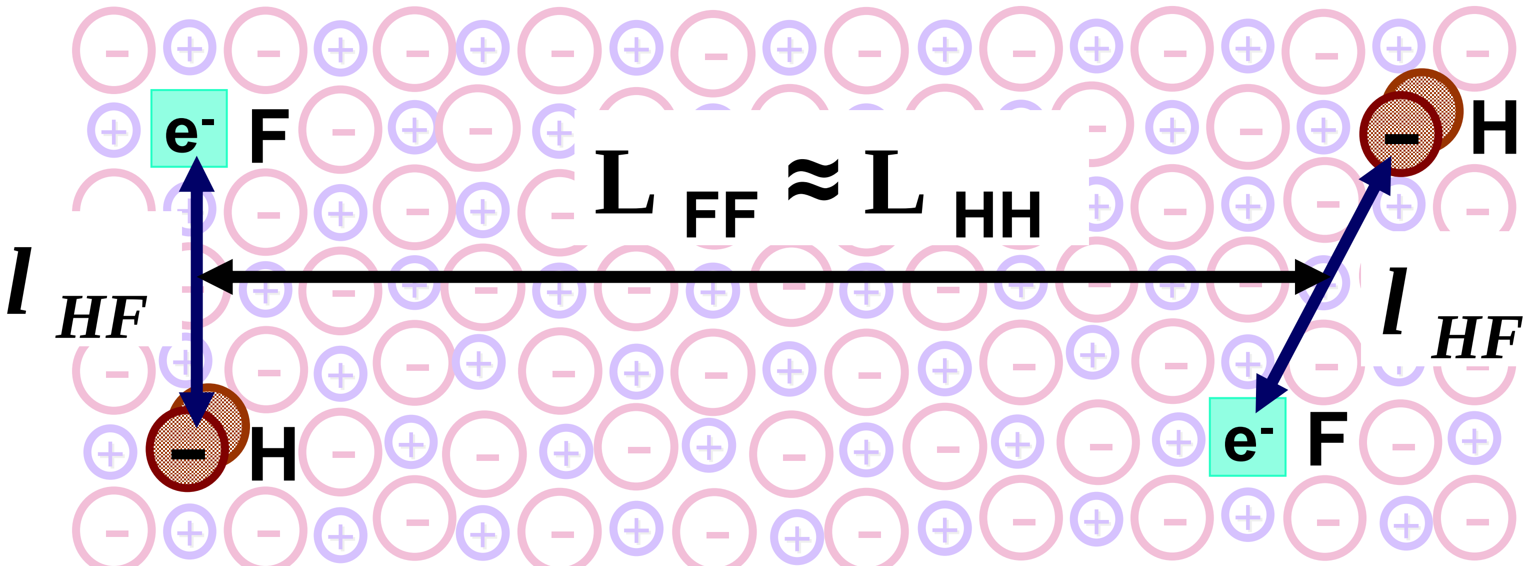


NaCl



Defect separation lengths

Two lengths governing defect recombination and aggregation, *NIM B 245 (2006) 204*

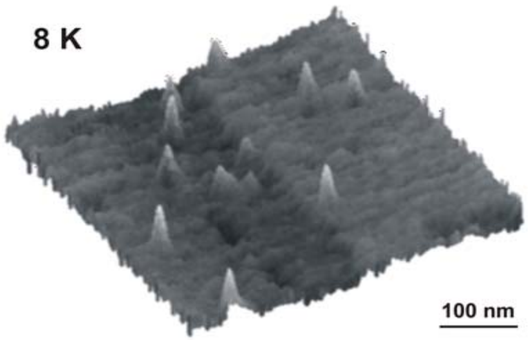


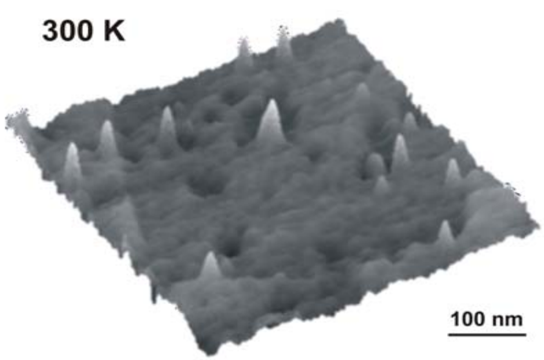
Separation of F and H centers in Frenkel pairs depends on local temperature during pair creation; Lushchik et al.(1992); Spaeth et al.(1994)

$$l \sim \sqrt{6 D_H \tau} \geq l_{HF}^{\min} = 5a = 1.4\,nm$$

Hillocks in LiF Irradiated with 1400 Pb ions at 8 K and 300 K

M. Lang et. al. Phys. Stat. Solidi (c) 4(2007) 1105





1. Determined by aggregates (track core damage)
2. Threshold dE/dx ~ 6 keV/nm
3. No dependence on T_{irr}

8 K

d = 19.5 ± 3 nm

h = 0.9 ± 0.2 nm

300 K

d = 18.3± 3 nm

h = 0.8 ± 0.2 nm

NaCl,

NIM B 225 (2005) 397

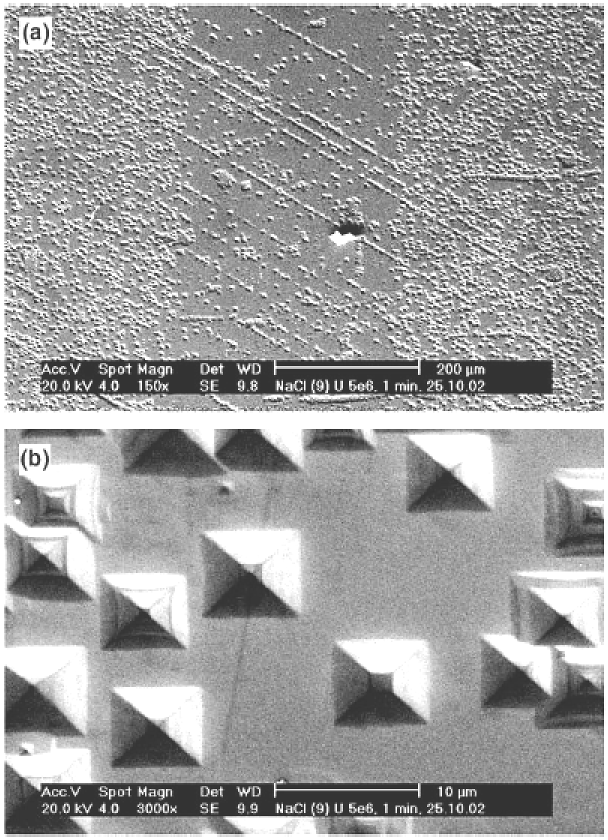


Fig. 4. SEM images at low (a) and high (b) magnification showing a NaCl surface irradiated through a structured mask with 11.1 MeV/u U ions (5×10^6 cm^{-2}). After 1 min of room-temperature etching, masked (vertical central stripe) and irradiated areas can be recognized (a). Etch pits resulting from ion tracks (b) exhibit the same shallow pyramidal shape as etched dislocations in the masked area.

LiF,Dislocation density

NIM B 209 (2003) 93

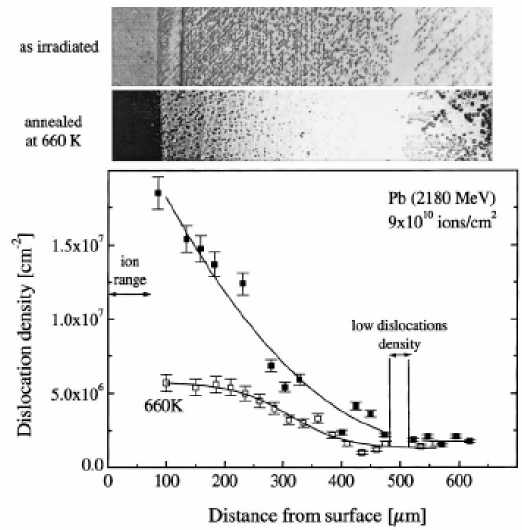
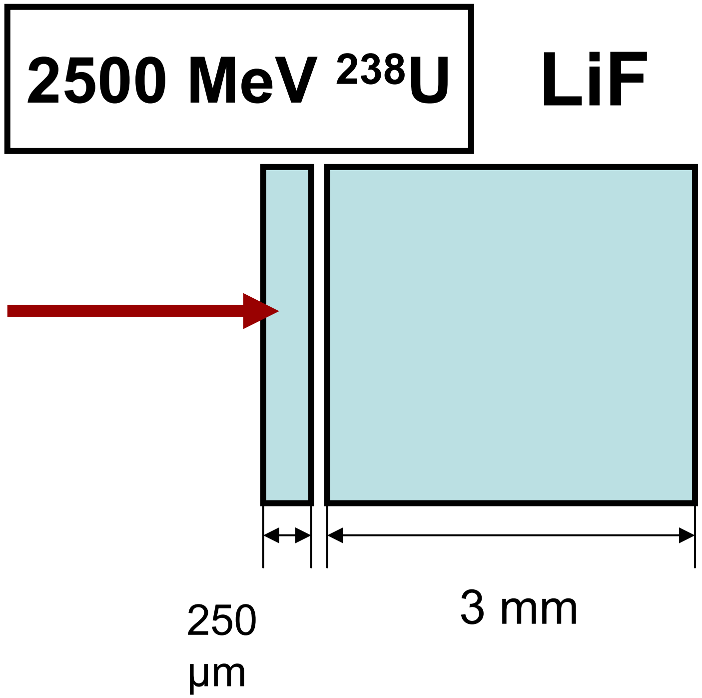
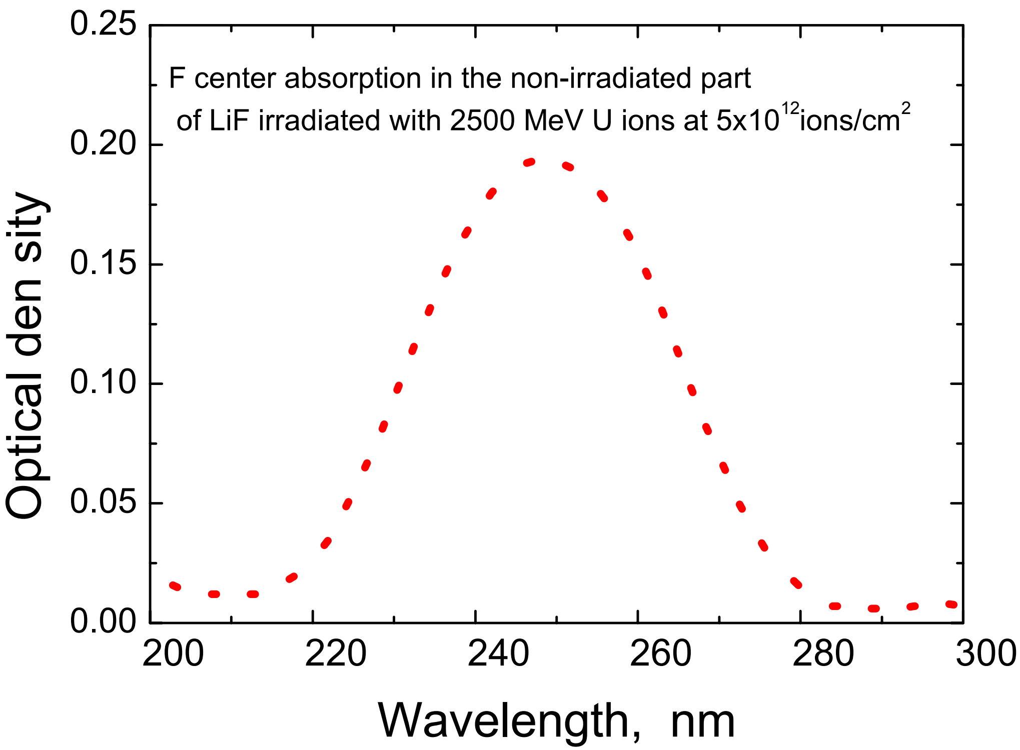
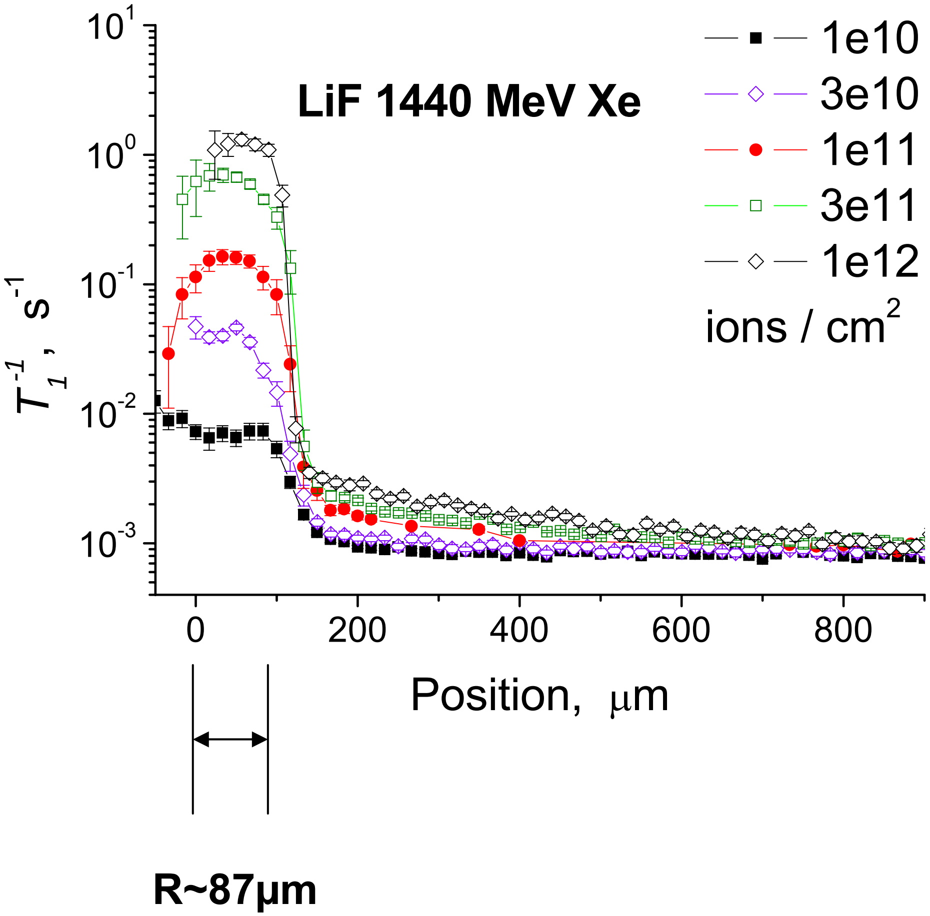


Fig. 9. Dislocations on etched cross-sections of crystals irradiated with 2180-MeV Pb ions before (top) and after (center) annealing at 660 K. The length scale of the micrographs correspond to the x-axis of the plot (bottom) with dislocation density as a function of sample depth.


2500 MeV 238U
LiF
250
µm
3 mm


F center absorption in the non-irradiated part
of LiF irradiated with 2500 MeV U ions at 5x10^12 ions/cm^2
Optical den sity
Wavelength, nm
0.00
0.05
0.10
0.15
0.20
0.25
200
220
240
260
280
300

Spatially resolved field gradient NMR, H. Stork et al.



$T_1^{-1} \sim n_F$

k = (irradiated) /

(non – irradiated)

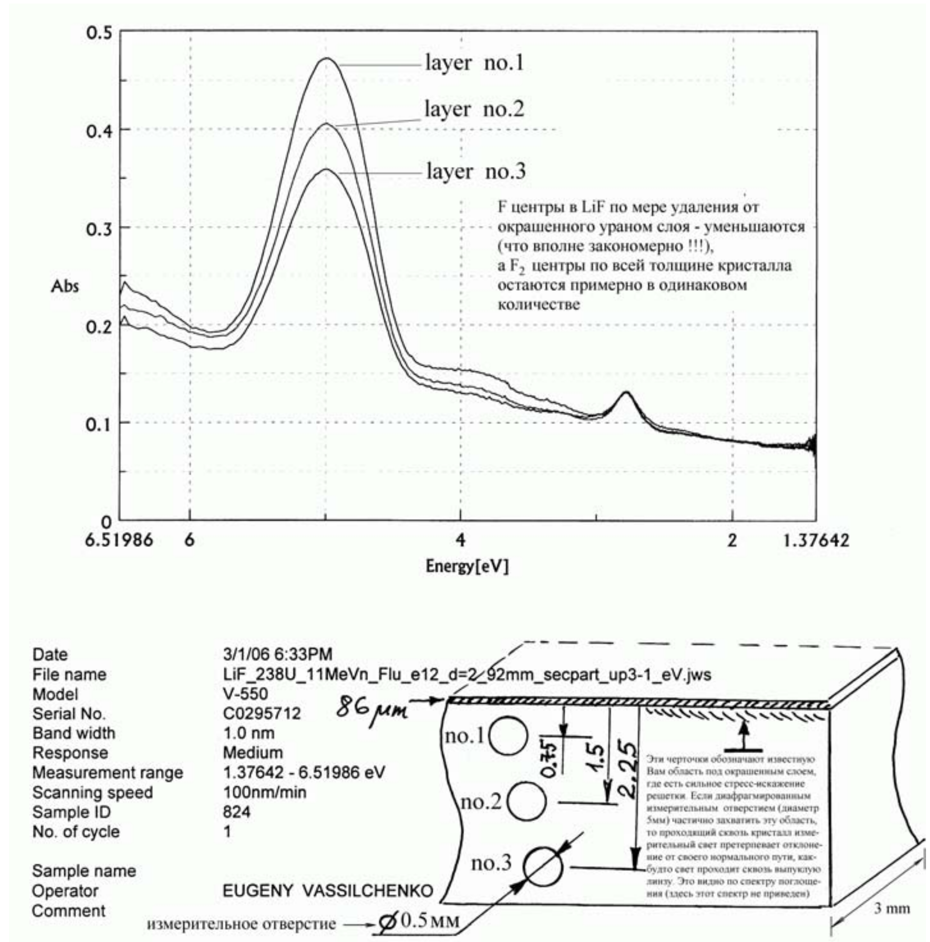
$k \sim 10^3$

F center concentration in the depth beyond the track: decreasing with the thickness

X- ray absorption

$$I = I_0 e^{-\mu d}$$

$$n_F(x) \sim \exp(-x/l)$$

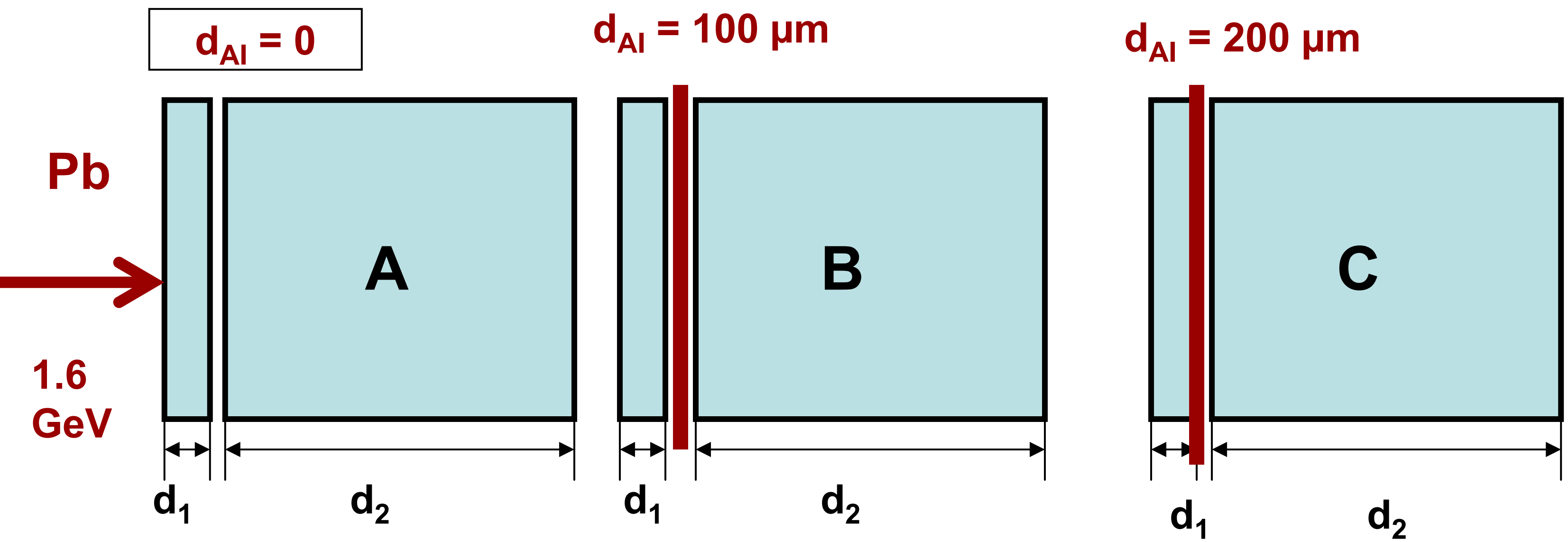


Exponential decrease of the X – ray intensity

$$n_F \sim I_x$$

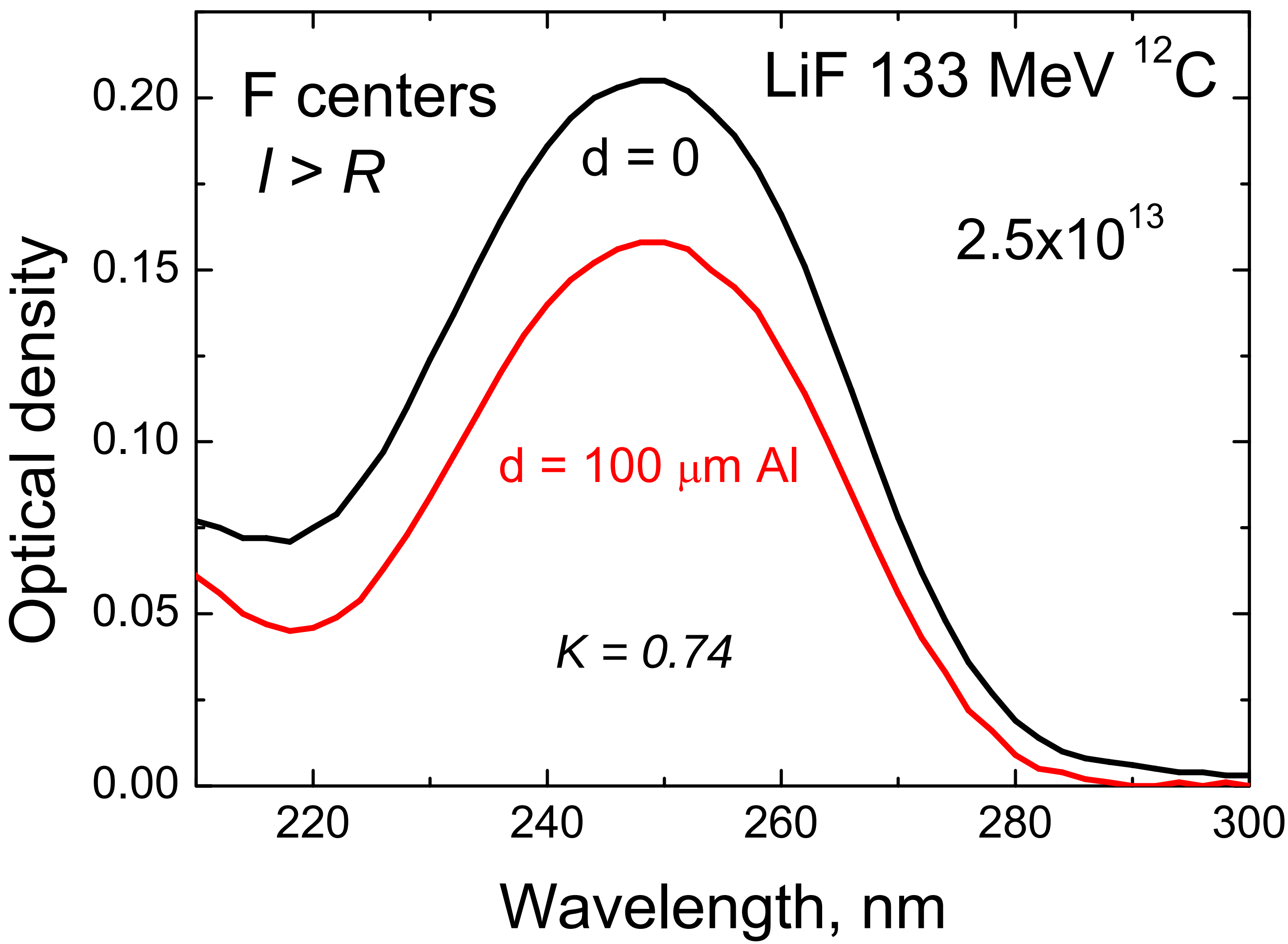
Irradiation with 130 MeV ^{12}C ions trough Al films

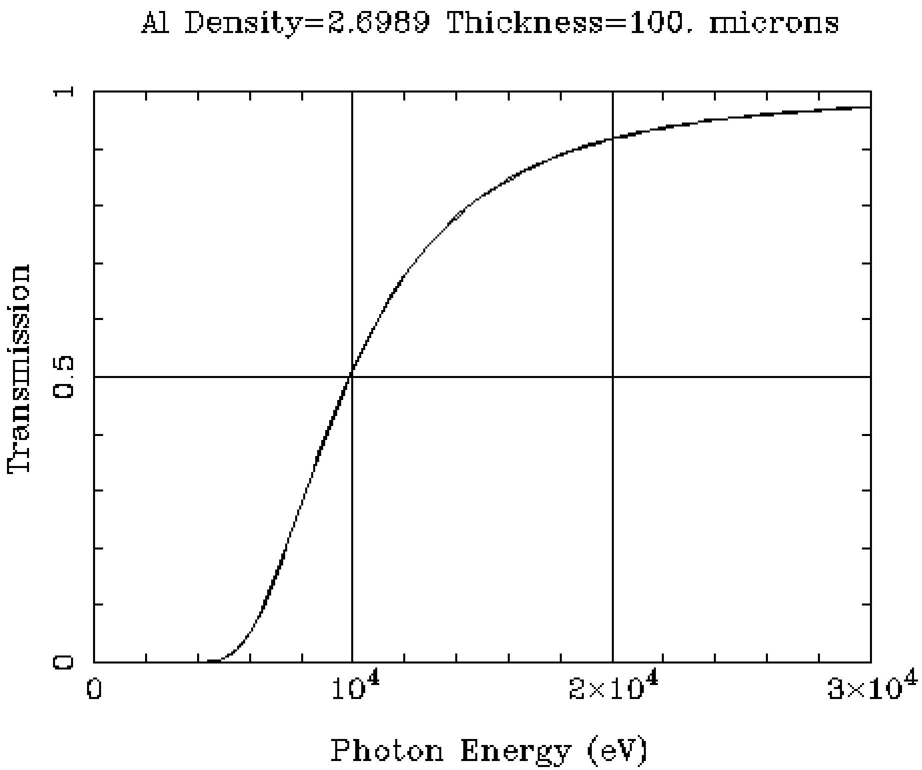
$E_{\delta}^{nax} \sim 16.7$ keV



$d_1 \approx 300$ μm; $d_2 \approx 3000$ μm = 3 mm

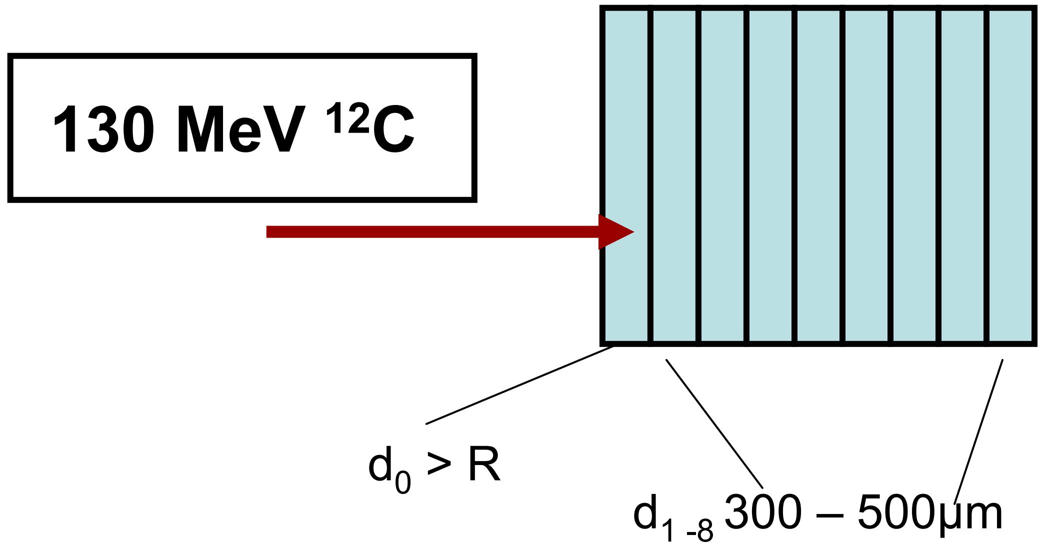
$k_1 = D(B) / D(A)$; $k_2 = D(C) / D(A)$

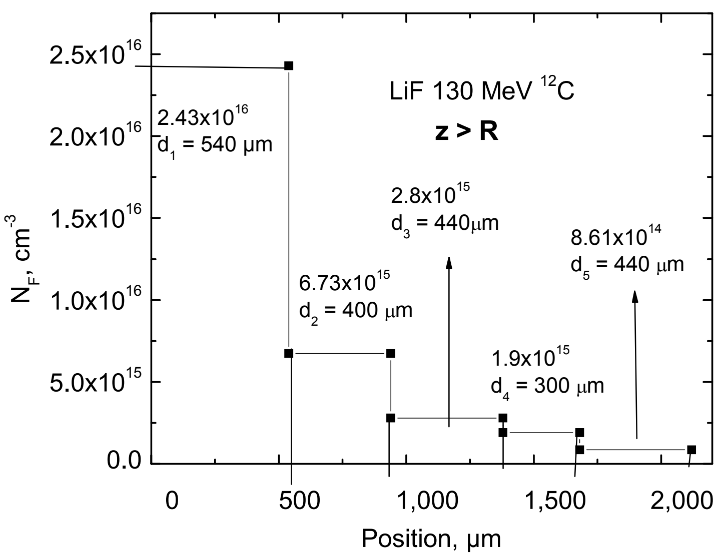

F centers
l > R
LiF 133 MeV ^{12}C
d = 0
$2.5x10^{13}$
d = 100 μm Al
K = 0.74
Optical density
0.00
0.05
0.10
0.15
0.20
220
240
260
280
300
Wavelength, nm



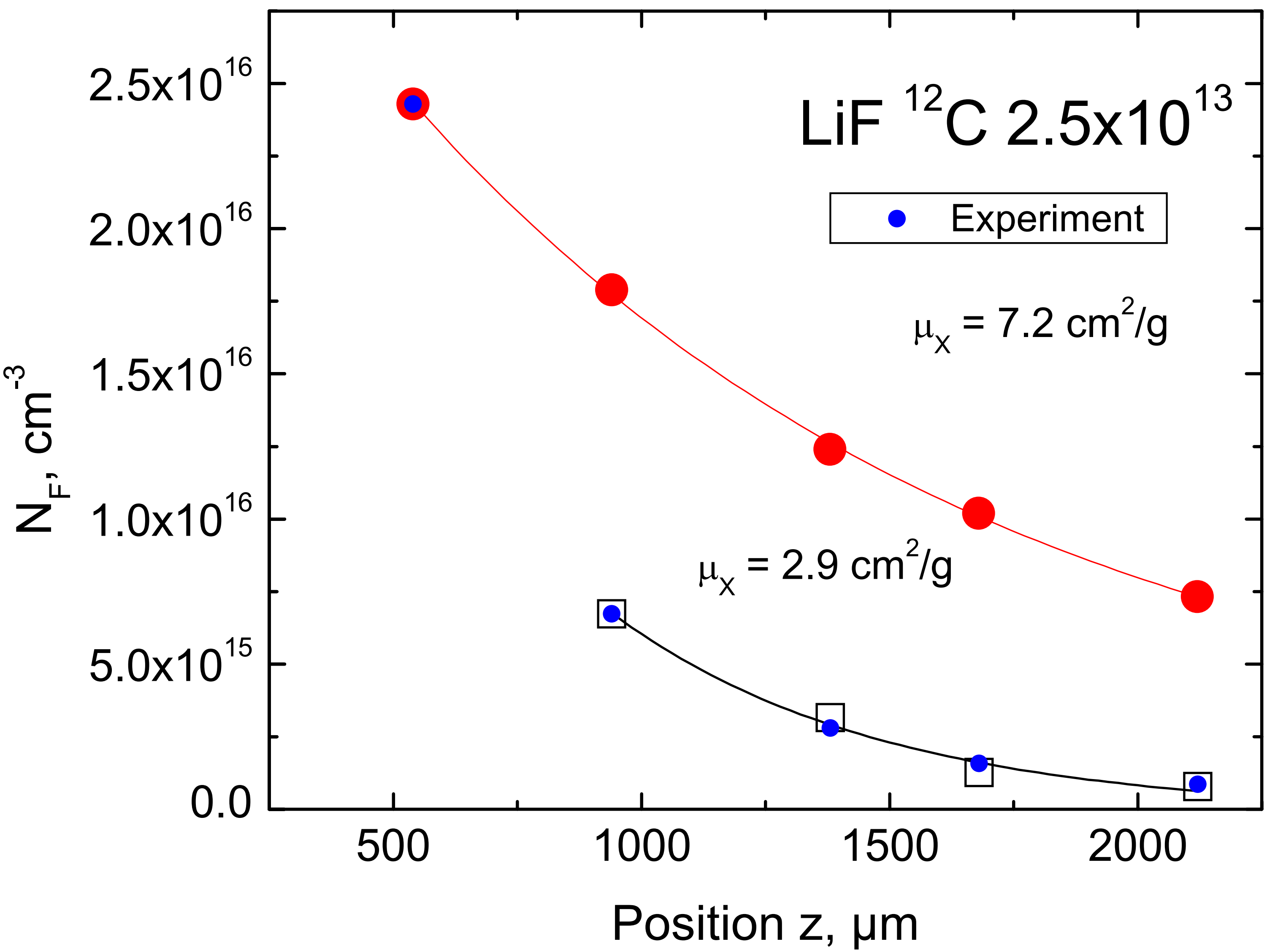
Transmission k = 0.74

$E_X \approx 13$ keV





$$N_F(z_i) = N_F(z_{i-1})\exp(-\mu_X \rho z)$$

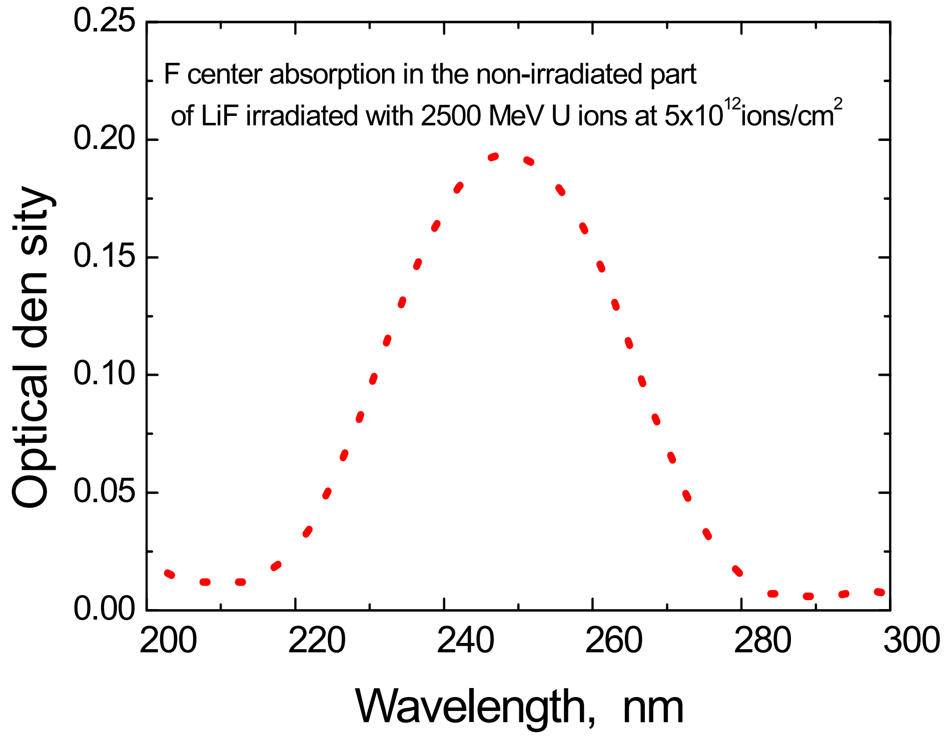


LiF ^{12}C $2.5x10^{13}$
Experiment
μ_X = 7.2 cm^2/g
μ_X = 2.9 cm^2/g
N_F, cm^{-3}
Position z, μm
0.0
$5.0x10^{15}$
$1.0x10^{16}$
$1.5x10^{16}$
$2.0x10^{16}$
$2.5x10^{16}$
500
1000
1500
2000

2500 MeV U – ion induced F center absorption

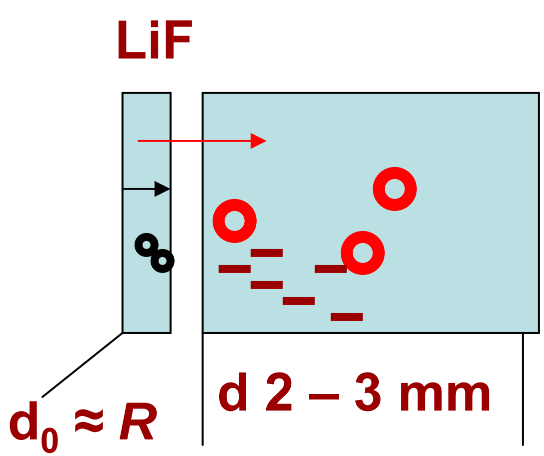
Similar results with Pb, Au, Xe, etc.

F centers can be detected at
$\Phi \geq 3x10^{11}$ ions/cm^2



$n_F = 1.8x10^{15}$ cm^{-2} ; $n_F(z > R)/n_F(z < R) \approx$ **10^{-3}**

Defects beyond the track *z* > *R*



Defect creation processes

- X-rays from δ electrons ≤ 24 keV
- X-rays from projectile electrons ≤ 6 keV
- Elastic recoil atoms, l_i *large*
- Fission products and neutrons
- Nuclear reaction fragments and neutrons

Experiments with ions:

12-C 130 MeV *R = 245 µm* 2.5x10^{13}

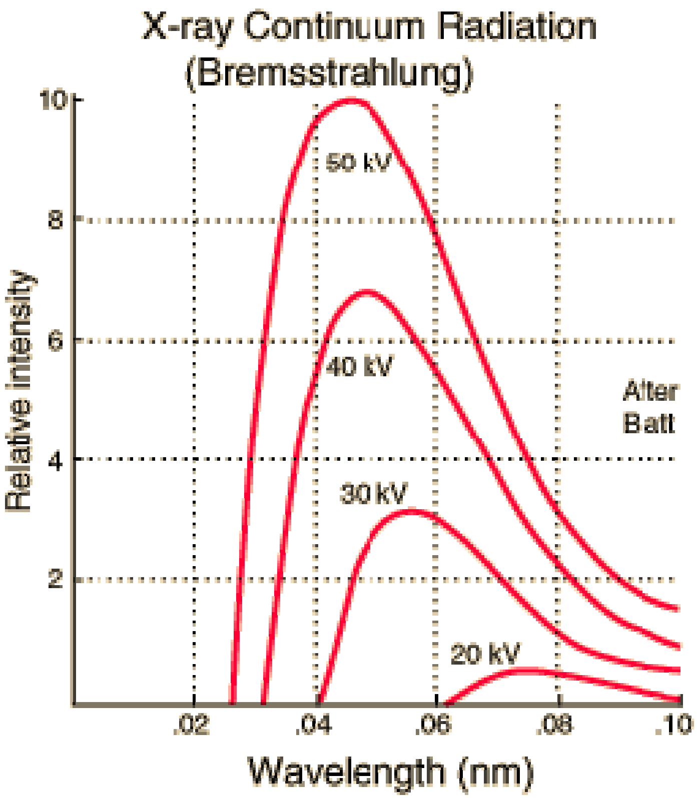
130-Xe 135 MeV *R = 80 µm* 5x10^{12}

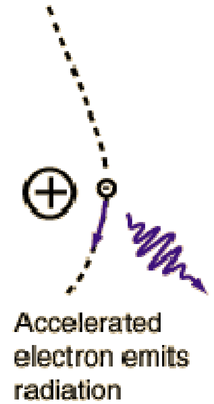
197-Au 2100 MeV *R = 95 µm* 5x10^{12}

208-Pb 1600 MeV *R = 69 µm* 2x10^{12}

238-U 2500 MeV *R = 89 µm* 5x10^{12}

Bremsstrahlung Spectrum





12 keV corresponds to 0.1 nm

Conclusions

1. Alkali halides, especially LiF is an excellent model for damage studies under ion irradiation
2. New phenomena were observed in LiF under ion irradiation(dependences on dE/dx,T_{irr}, E_{ion}, etc.)
3. The color centers beyond the track can be produced by various processes: X-rays; recoil atoms; nuclear reaction fragments
4. Damage creation beyond the ion track, probably, takes place in any solid
5. Additional experiments are necessary to clear the mechanisms of defect creation beyond the track

Colaboration

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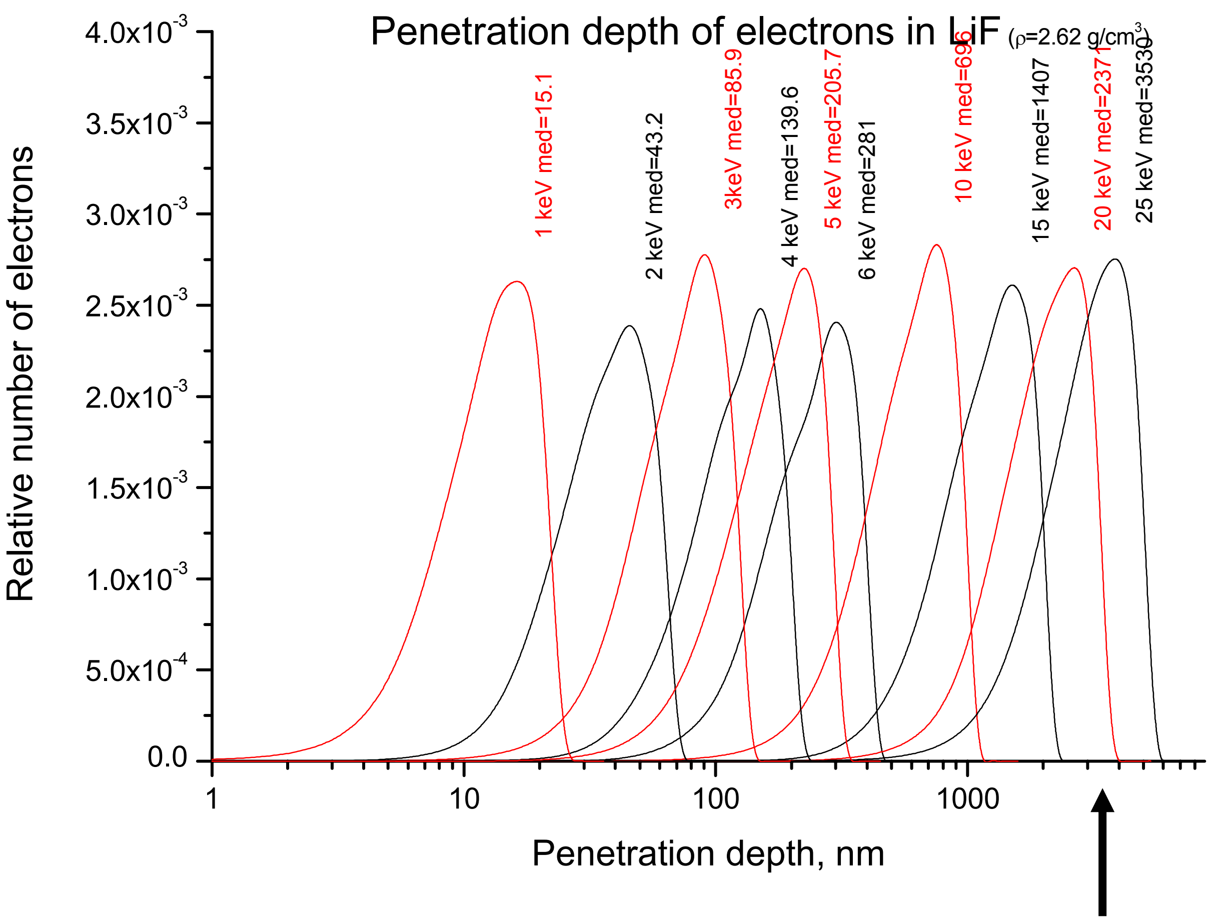
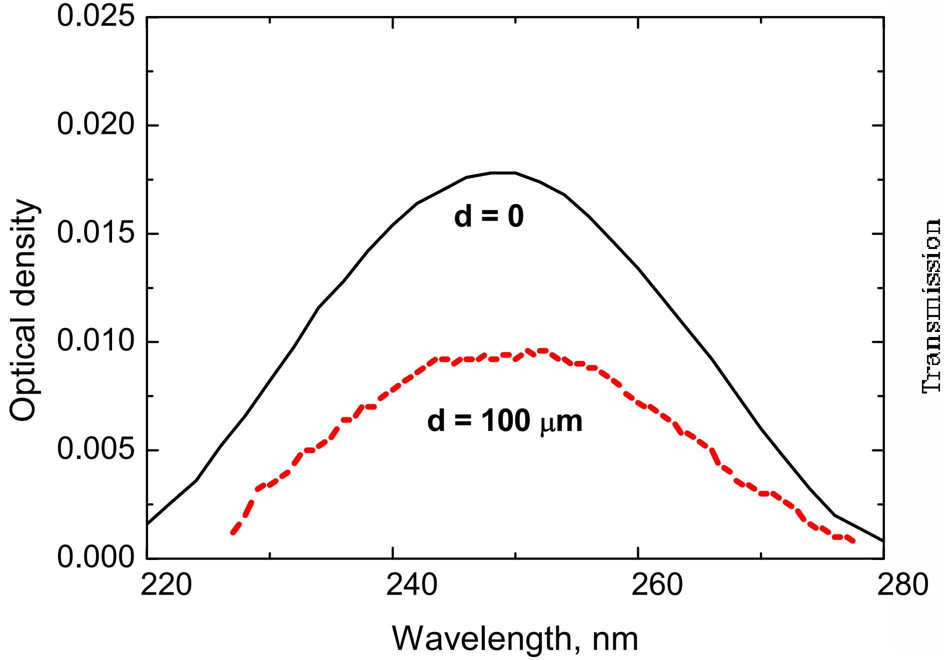
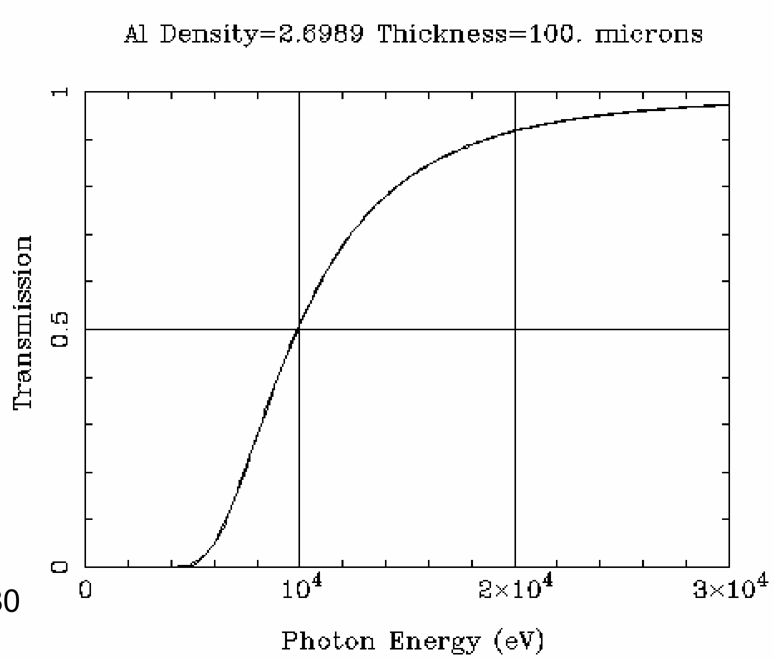
Thank you for your attention

Penetration depth of δ electrons



Transmission of the radiation





$k_1 = 0.61 \pm 0.07$ $k_2 = 0.50 \pm 0.07$; $h\nu_x = 12 \pm 2$ keV

F center concentration in the depth beyond the track: decreasing with the thickness

X- ray absorption

$$I = I_0 e^{-\mu d}$$

$$n_F(x) \sim \exp(-x/l)$$

Exponential decrease of the X – ray intensity

$$n_F \sim I_x$$