ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

Optical Coatings Laboratory

Optical materials resistance in the Space environment

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Winter College on Optics
Light: a bridge between Earth and Space
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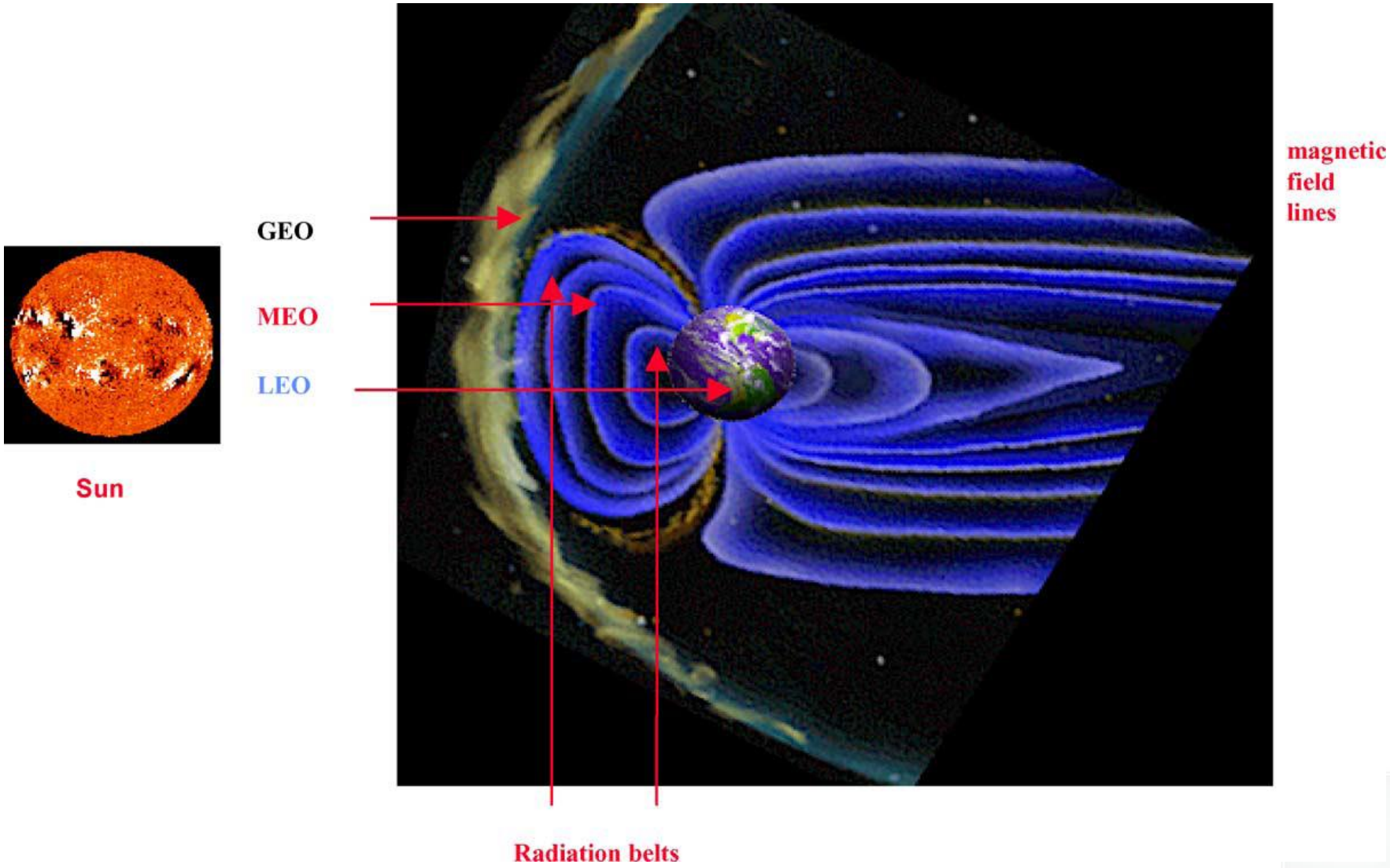
outline

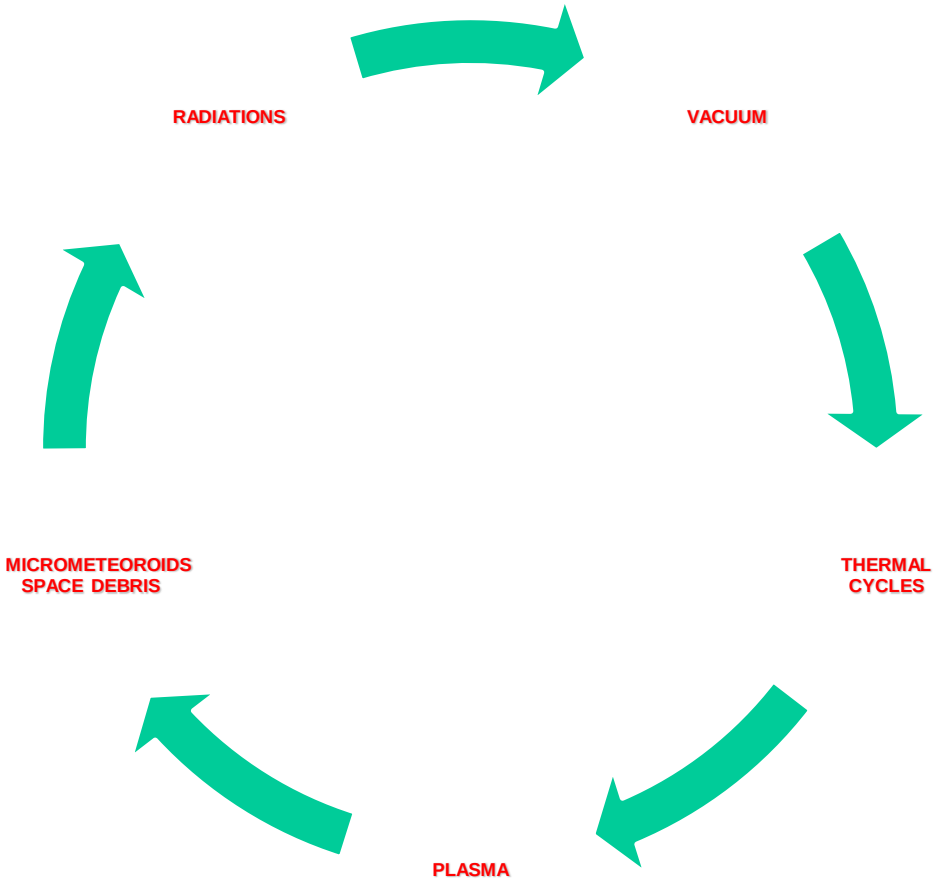
- Space radiation
- Low energy protons
- High energy protons
- Experimental results
- SRIM simulation of proton bombardment
- γ ray irradiation
- Atomic oxygen erosion (LEO)

Earth orbits

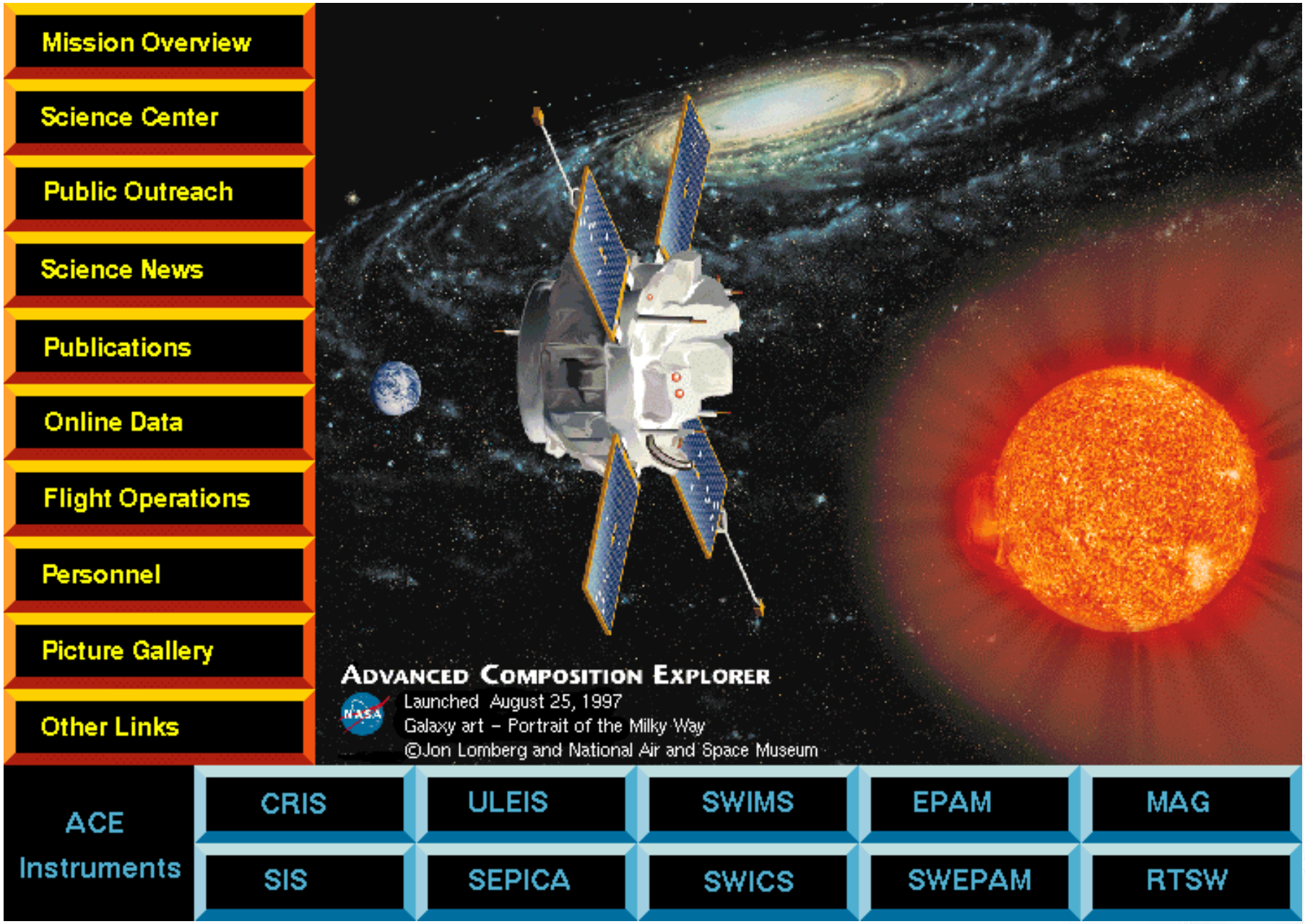


G. Pippin / Progress in Organic Coatings 47 (2003) 424–431

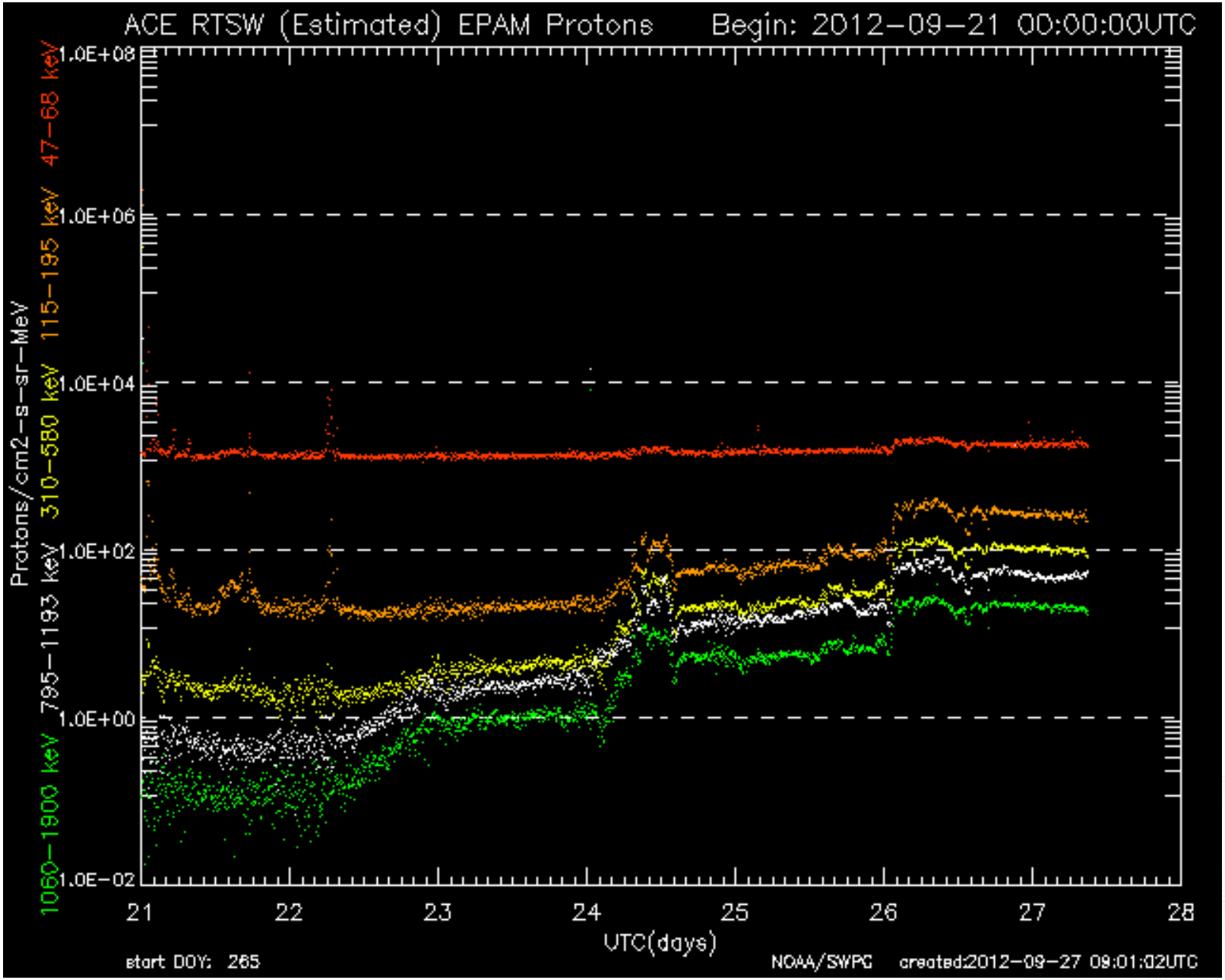
Space environment



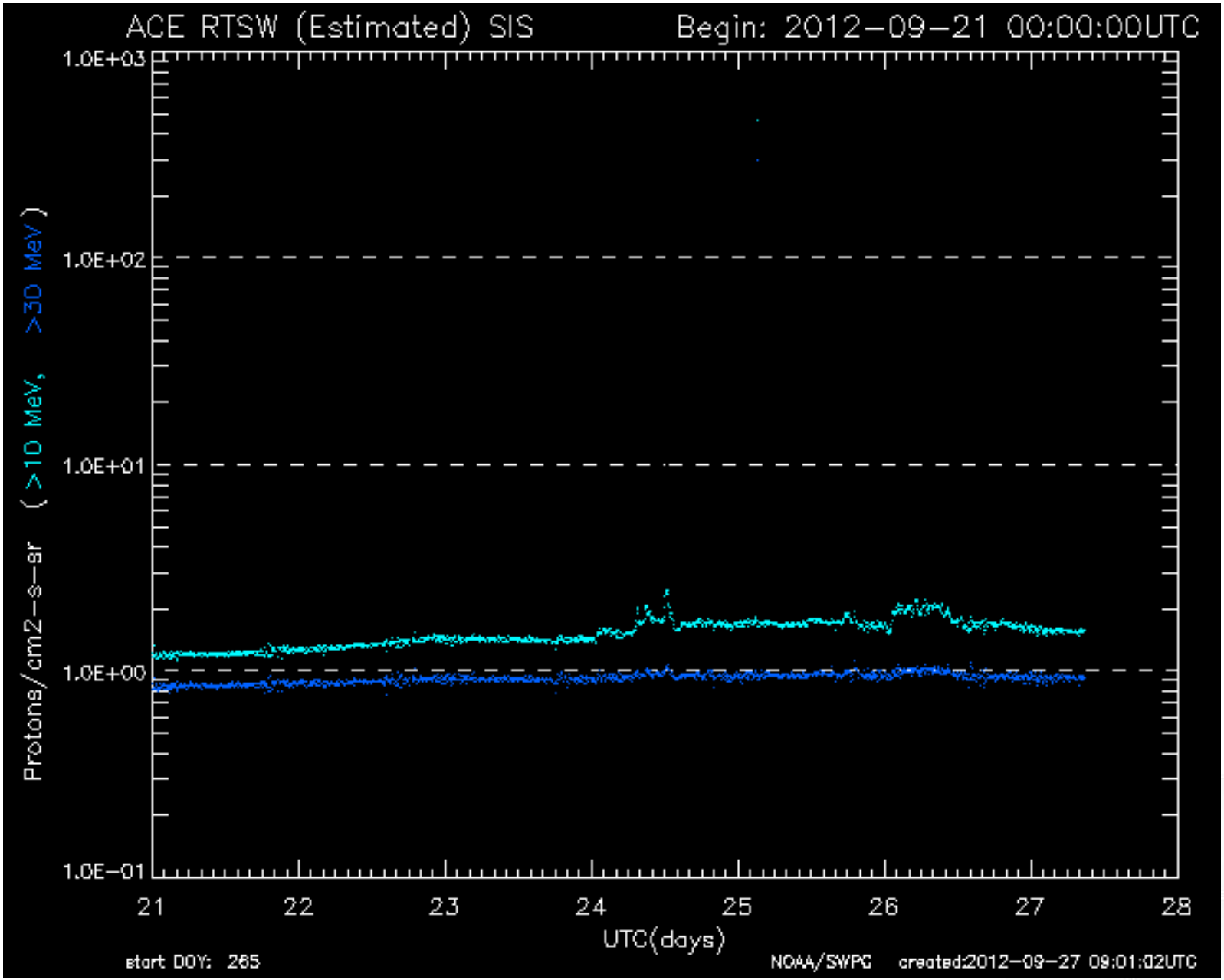
Space radiation: protons



Space radiation: low energy protons

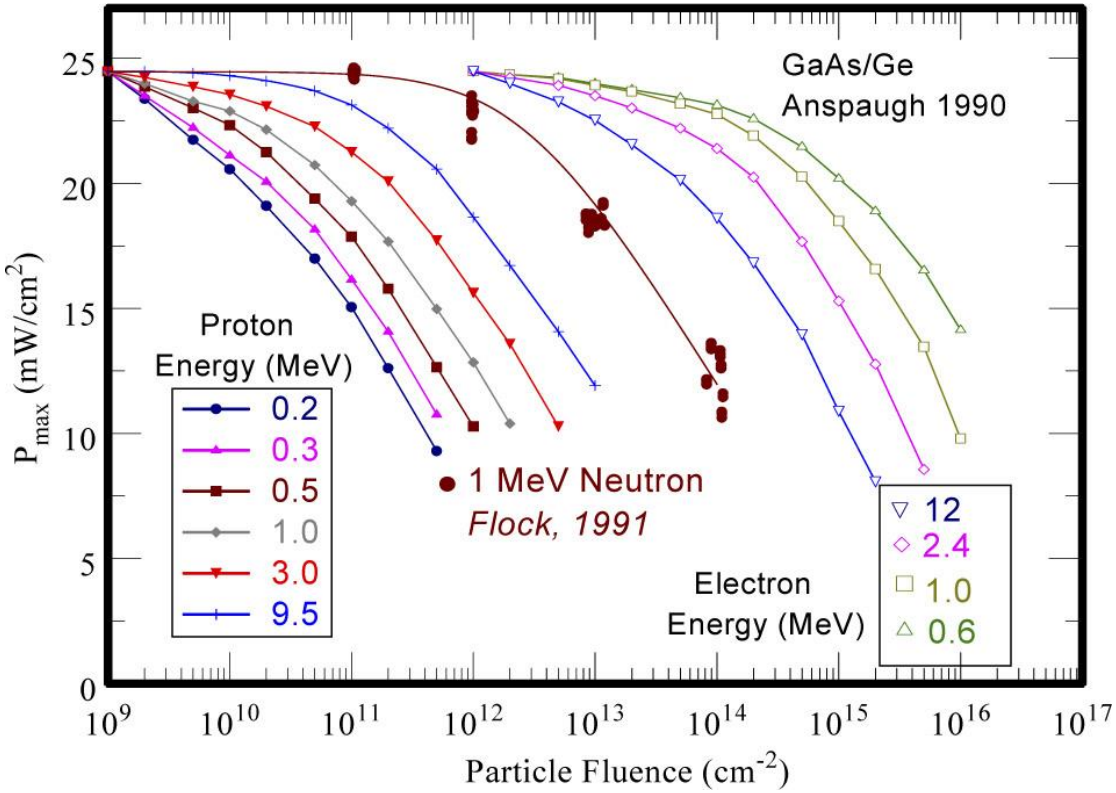


Space radiation: high energy protons 30 MeV



proton damage

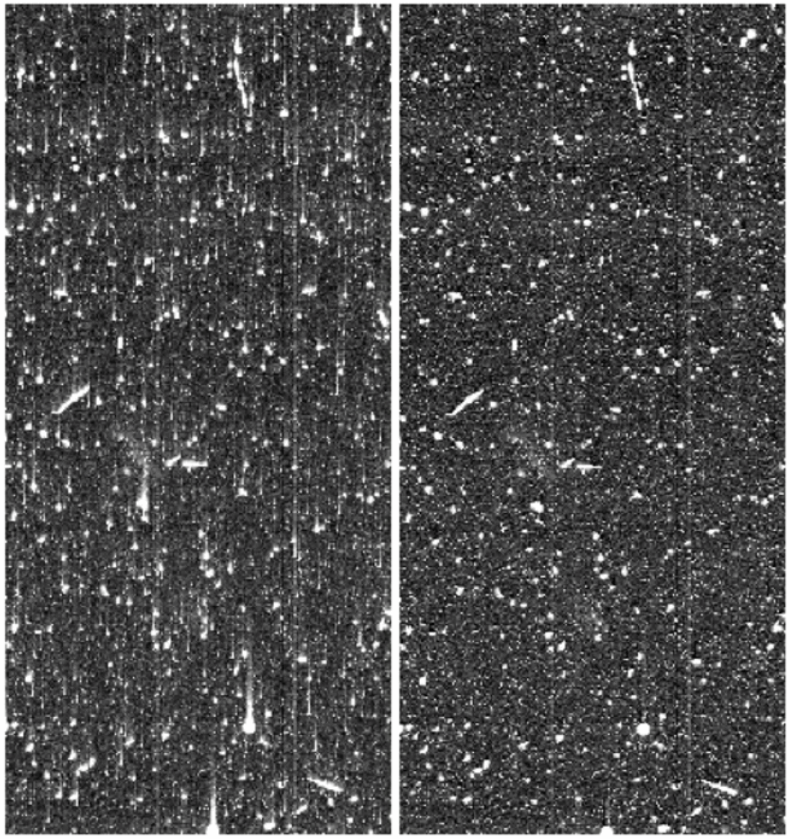
The two most well known elements of satellite systems most susceptible to damage by solar protons are micro-electronics and solar cells.



Robert J. Walters et al. SPIE, 10.1117/2.1201012.003417

Charge Transfer Inefficiency (CTI)

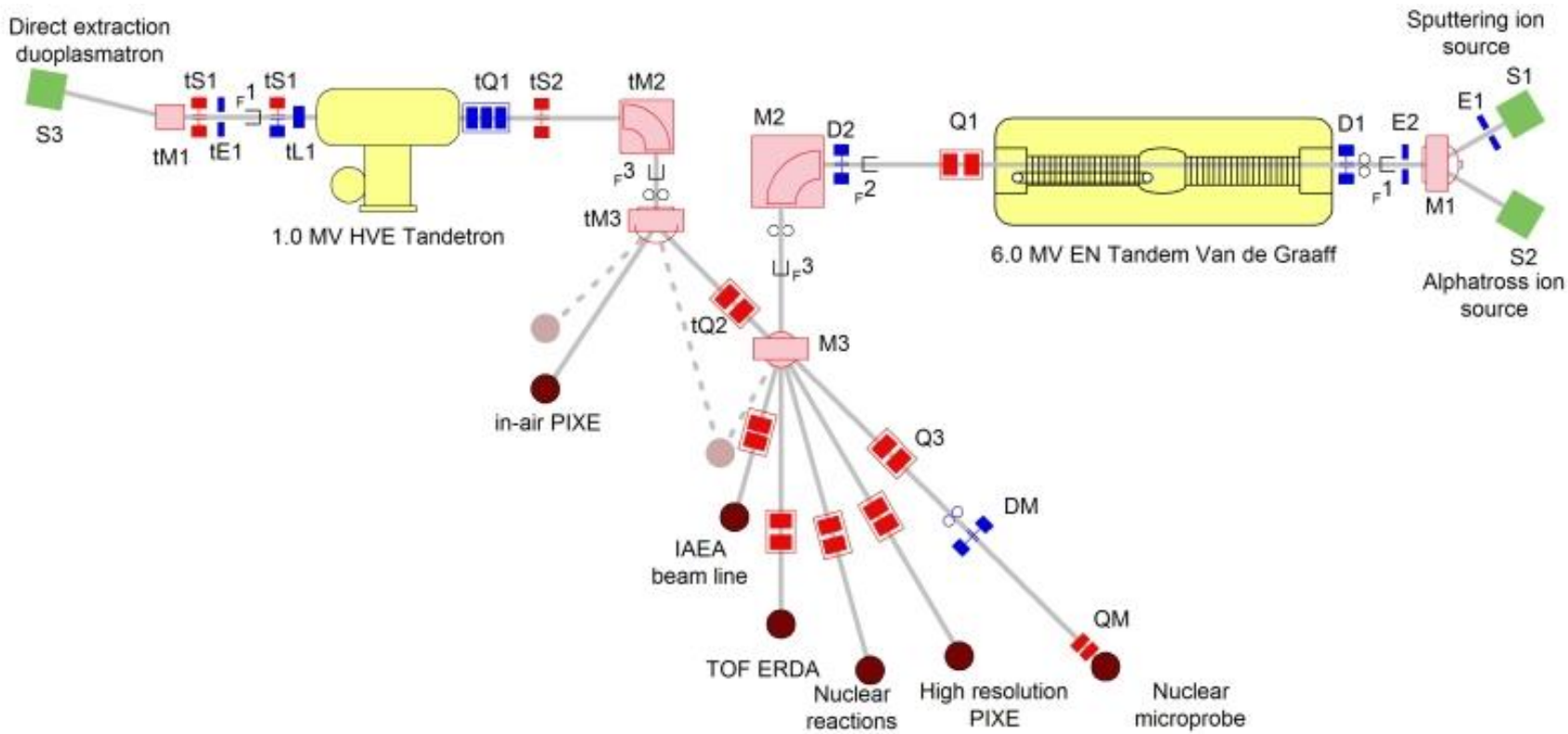
Image smearing caused by CTI in a Hubble Space Telescope image shown as the raw image (left) and after image correction has been applied (right). Hubble's radiation mitigation strategy was unique, send up astronauts to replace the sensors. (R Masey)



(R Masey), Mon. Not. R. Astron. Soc. 000, 1–6 (2010)

low energie protons : 60 keV, fluence: 10^{13} p^+/cm^2

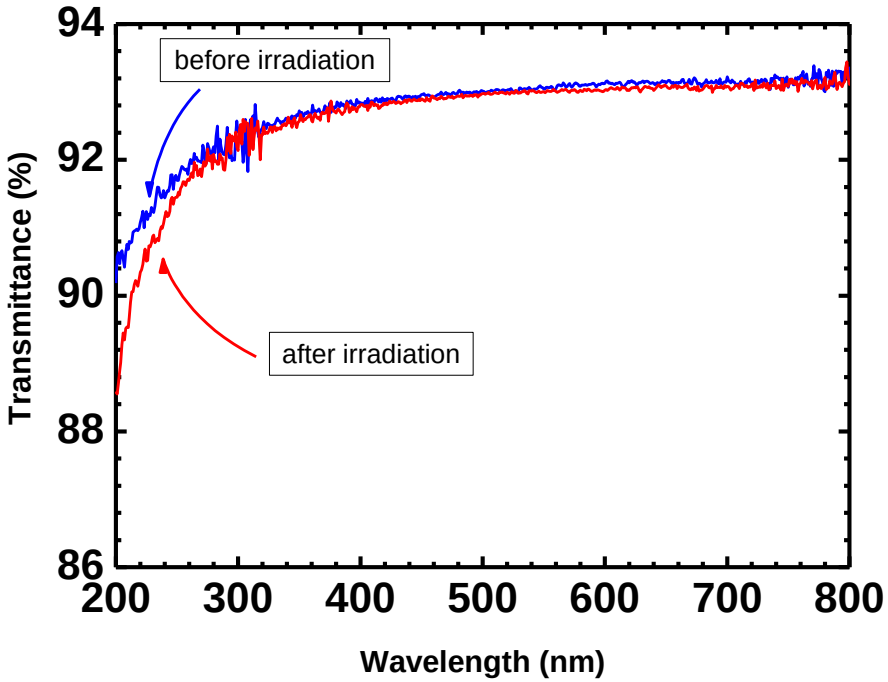
Rudjer Boskovic Institute, Zagreb, Croatia



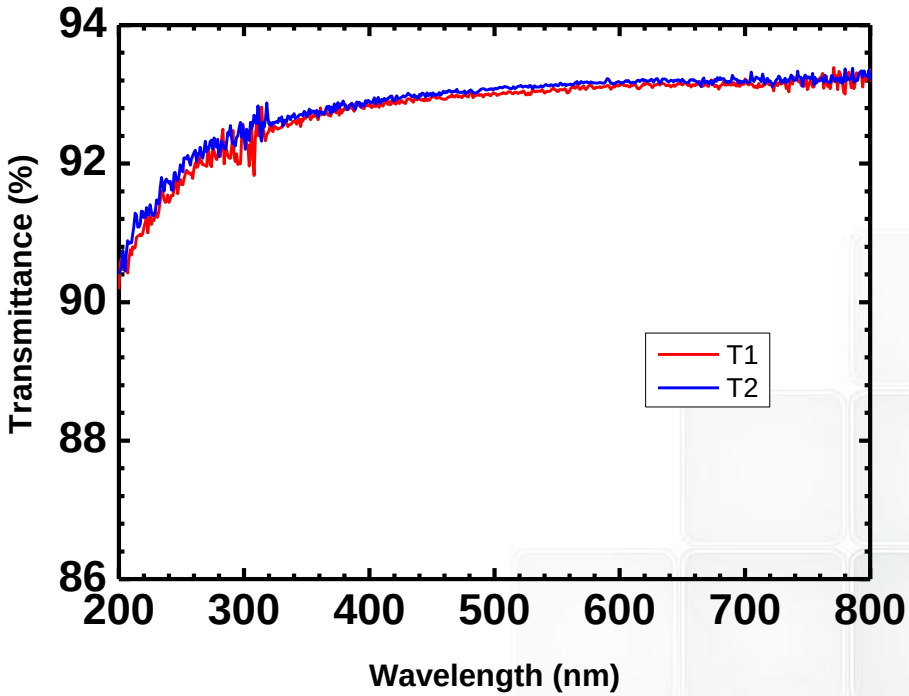
low proton energies : 60 keV, fluence: 10^{13} p^+/cm^2

Sample		
	Design	*Material (thickness)*
#1	substrate (thickness 1 mm)	Fused silica
#2	Single layer	HfO_2 (690 nm)
#3	Single layer	TiO_2 (720 nm)
#4	Fabry-Perot $[(HL)^7\ HH\ (LH)^7]$	$L=SiO_2$ $H=HfO_2$ $\lambda_0=316$ nm

fused silica (3mm) E(p⁺) = 60 Kev



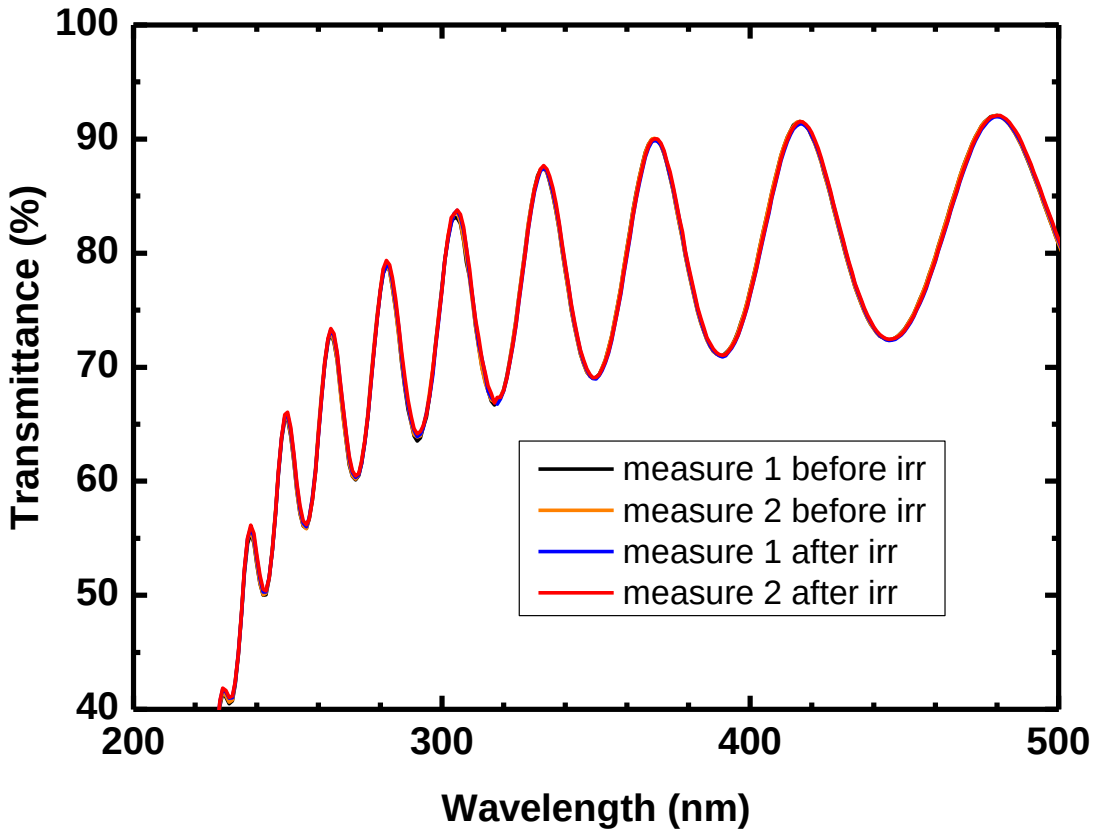
measurement errors



Comparison of fused silica transmittances.

low proton energies : 60 keV, fluence: 10^{13} p^+/cm^2

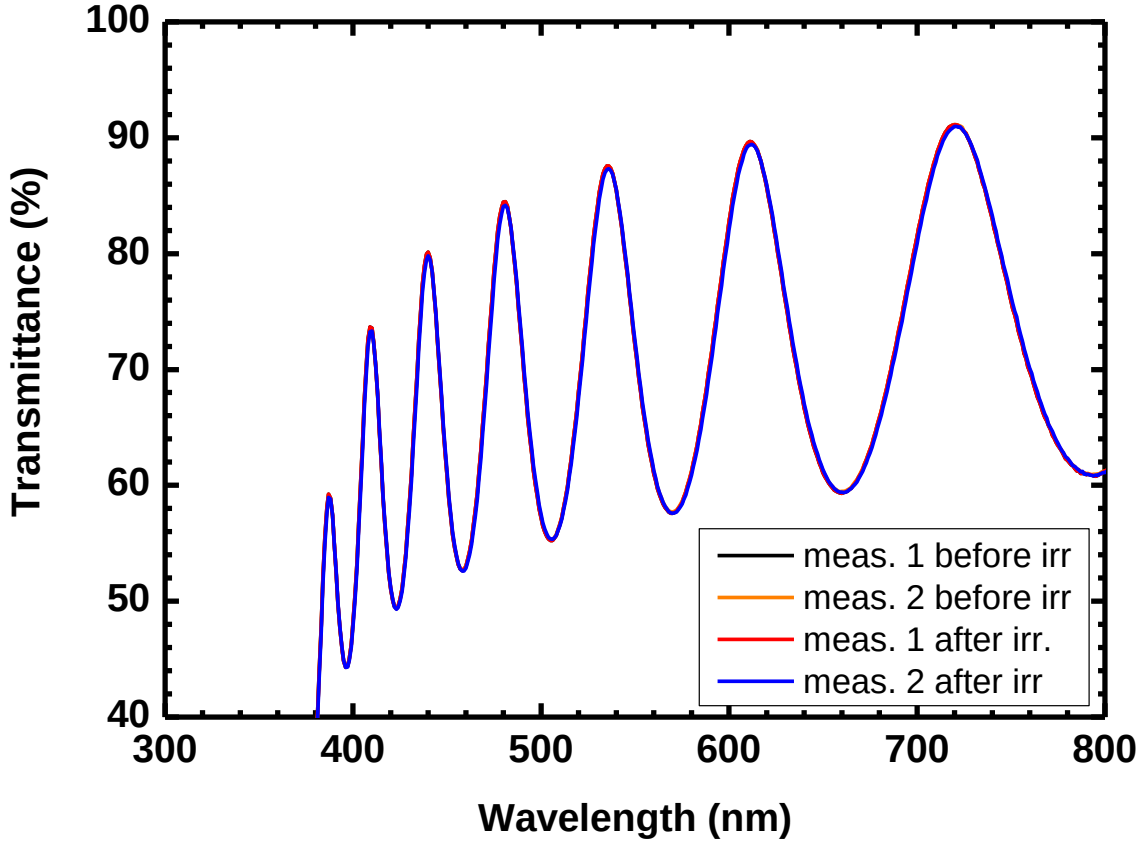
HfO_2 (690 nm)



Transmittance curves of HfO_2 layer (#2), before and after the proton irradiation.

low proton energies : 60 keV, fluence: 10^{13} p^+/cm^2

TiO_2 (690 nm)

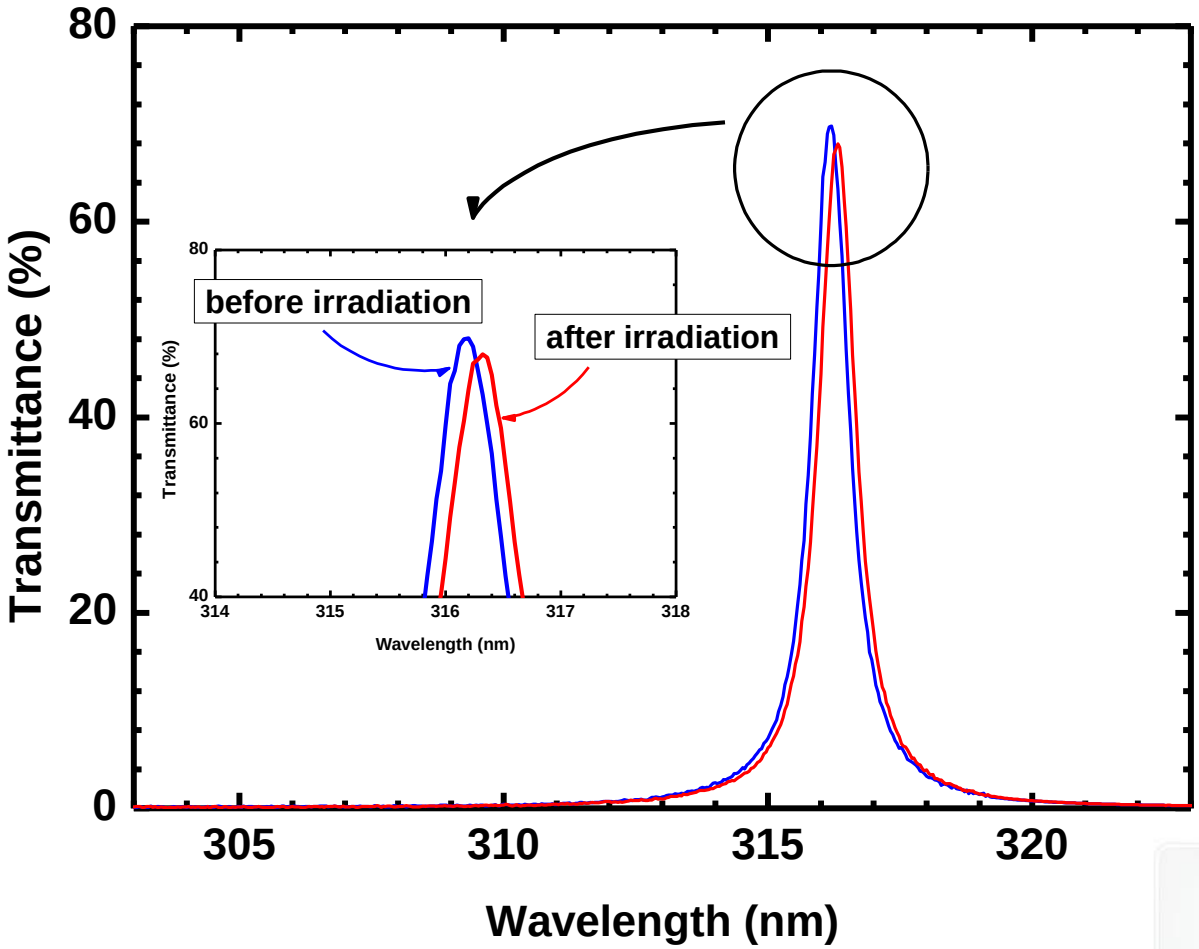


Transmittance curves of TiO_2 layer (#3), before and after the proton irradiation.

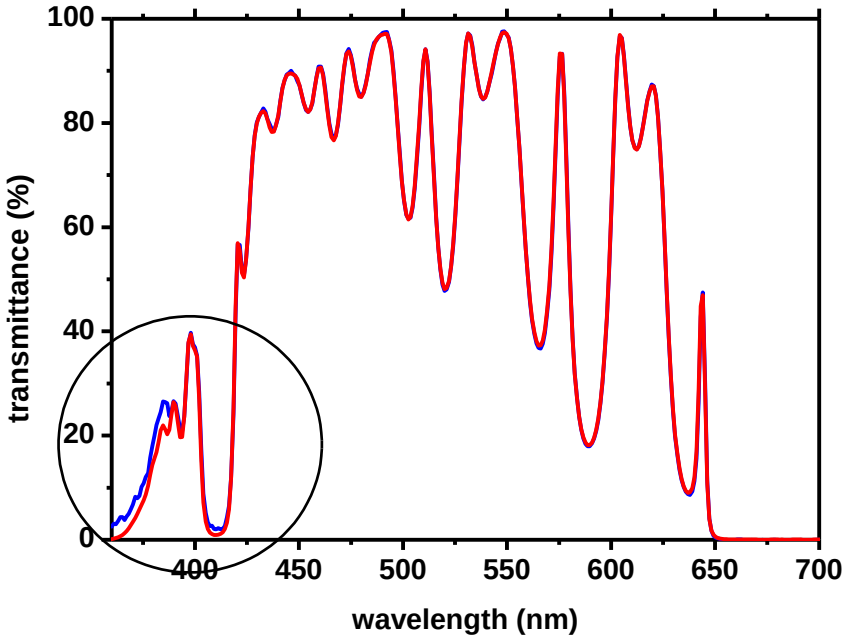
low proton energies : 60 keV, fluence: 10^{13} p^+/cm^2

Fabry-Perot
$(HL)^7$ HH $(LH)^7$

L = SiO_2
H = HfO_2



low energy protons: 60 keV, fluence: 10^{13} p^+/cm^2

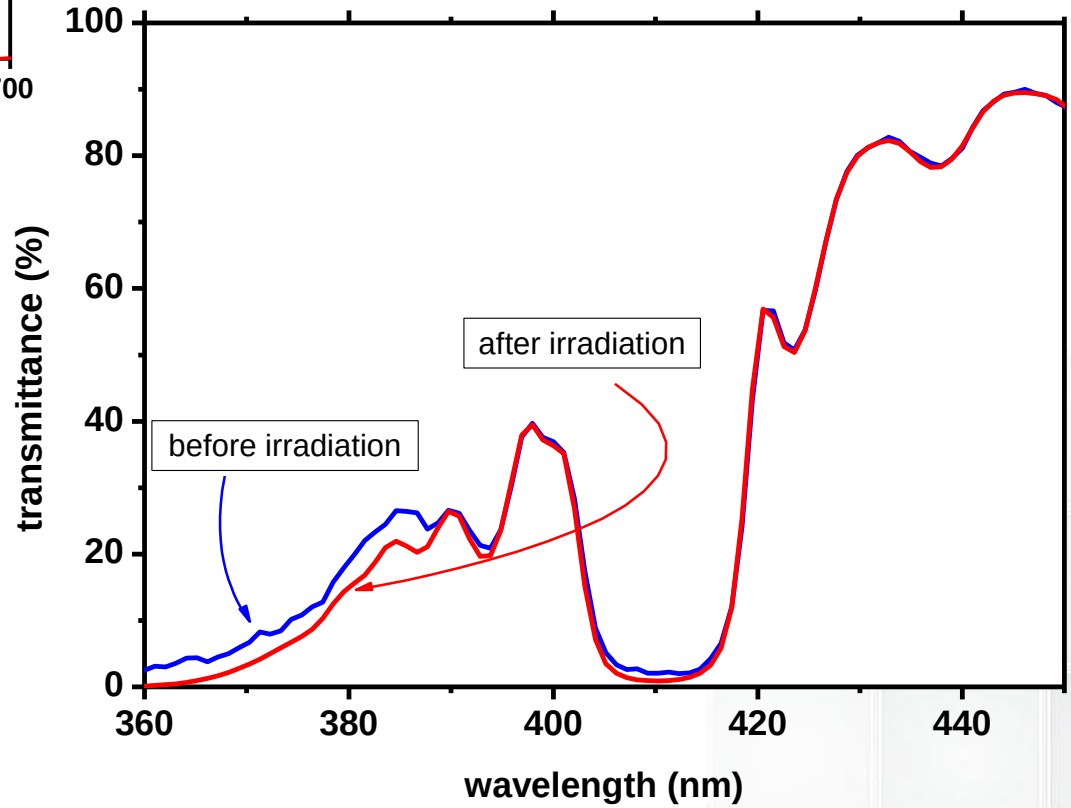


Double Cavity NBF

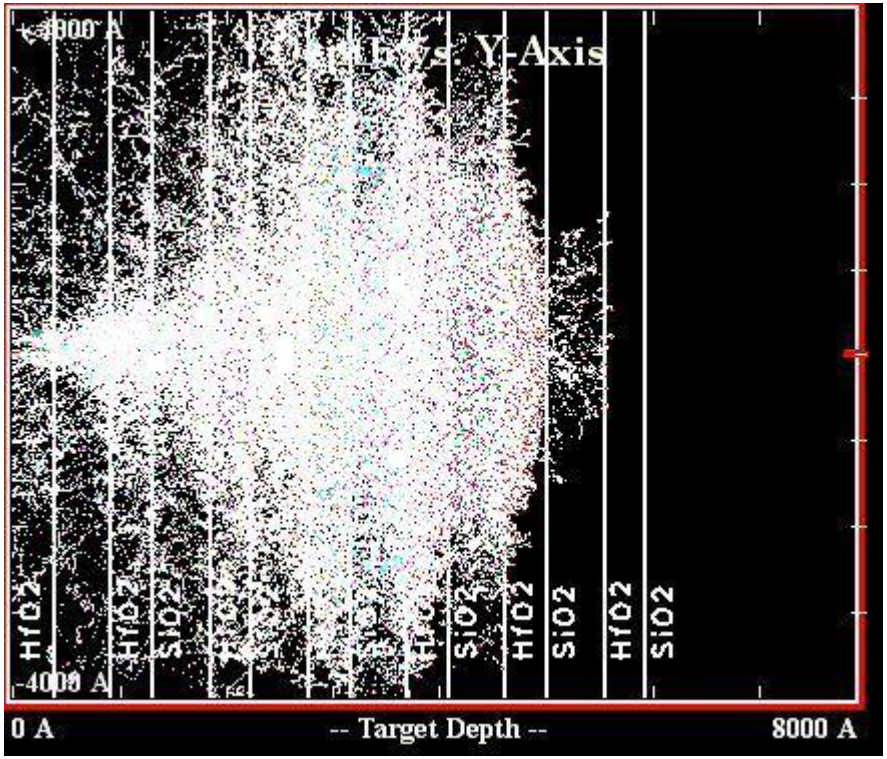
$(HL)^4$ HH $(LH)^4$ L $(HL)^4$ HH $(LH)^4$

L = SiO_2

H = TiO_2



proton damage : 60 keV, fluence: 10^{13} p^+/cm^2



SRIM 2013 (The **S**topping and **R**ange of **I**ons in the **M**atter)

Z_1 = atomic number of incident ion with energy E

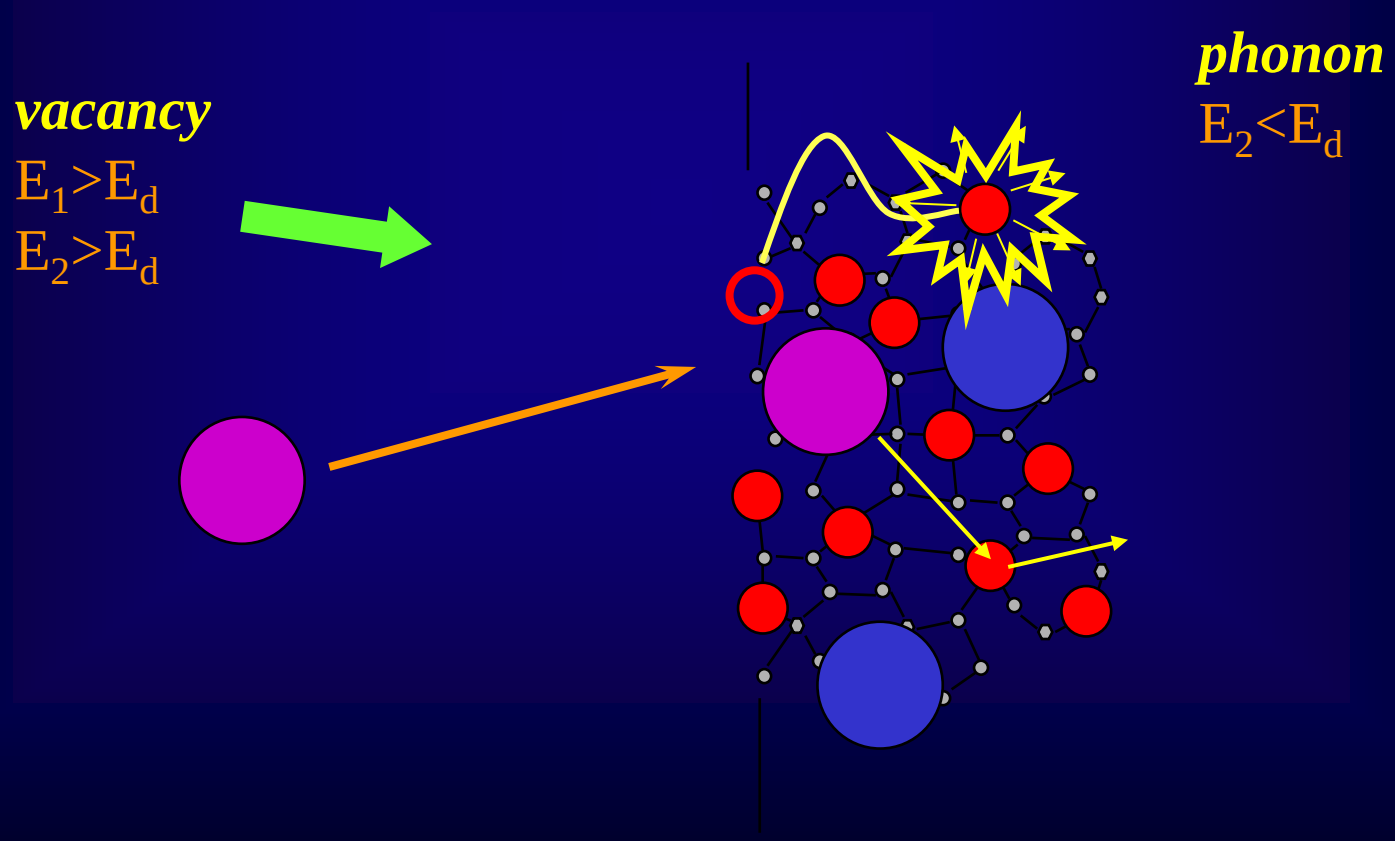
E_1 = energy of incident ion after the collision

E_2 = energy of struck atoms

E_d = displacement energy

J. F. Ziegler and J.P.Biersack, www.srim.org

A ***displacement*** occurs if E2>Ed (the hit atom is given enough energy to leave the site). A ***vacancy*** occurs if both E1>Ed and E2>Ed (both atoms have enough energy to leave the site). Both atoms then become moving atoms of the cascade. The energy, E2, of atom Z2 is reduced by Eb before it has another collision. If E2<Ed, then the struck atom does not have enough energy and it will vibrate back to its original site, releasing E2 as ***phonons***.



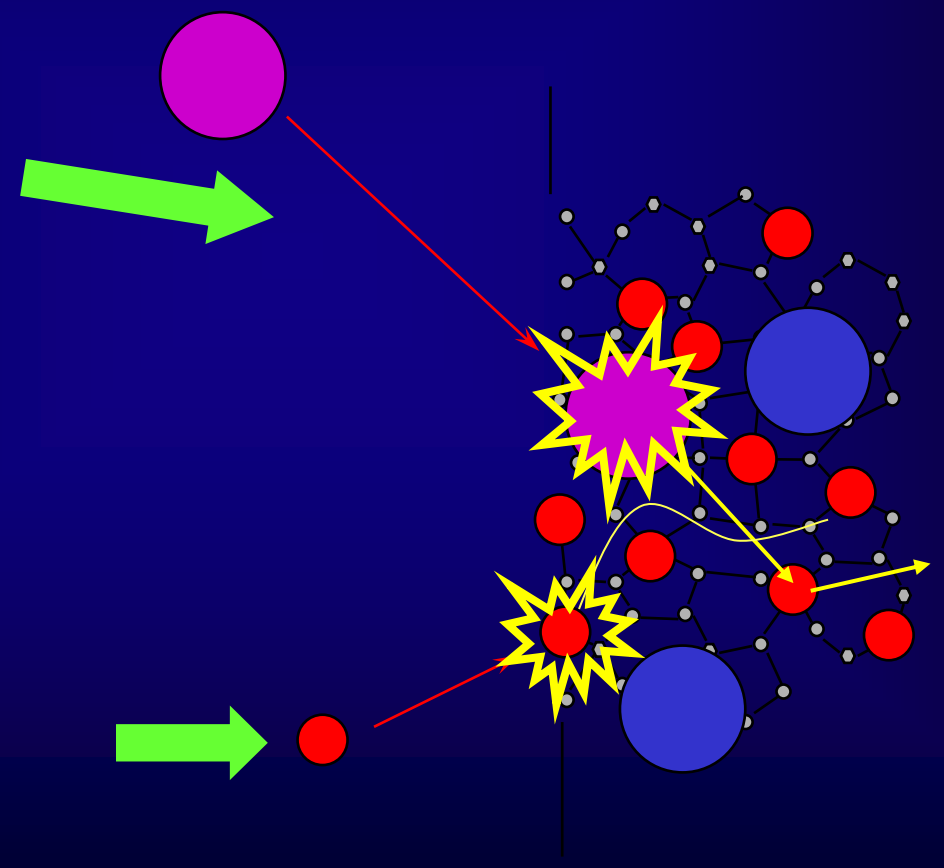
If E1<Ed and E2>Ed and Z1 = Z2, then the incoming atom will remain at the site and the collision is called a ***replacement collision*** with E1 released as ***phonons***. The atom in the lattice site remains the same atom by exchange. This type of collision is common in single element targets with large recoil cascades. If E1<Ed and E2>Ed and Z1≠Z2, then Z1 becomes a stopped ***interstitial*** atom.

interstitial

$Z_1 \neq Z_2$

$E_1 < E_d$ (phonon)

$E_2 > E_d$



substitutional

$Z_1 = Z_2$

$E_1 < E_d$ (phonon)

$E_2 > E_d$

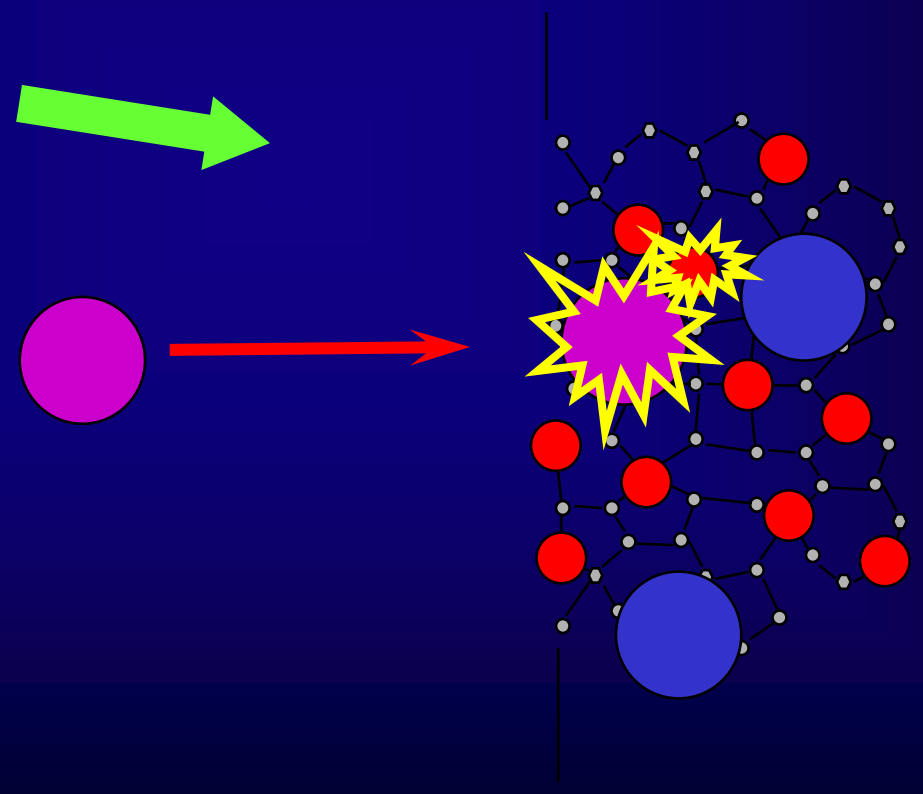
Finally, if E1<Ed and E2<Ed, then Z1 becomes an ***interstitial*** and E1+E2 is released as ***phonons***. If a target has several different elements in it, and each has a different displacement energy, then Ed will change for each atom of the cascade hitting different target atoms.

interstitial

$E_1<E_d$

$E_2<E_d$

E_1+E_2 (fononi)

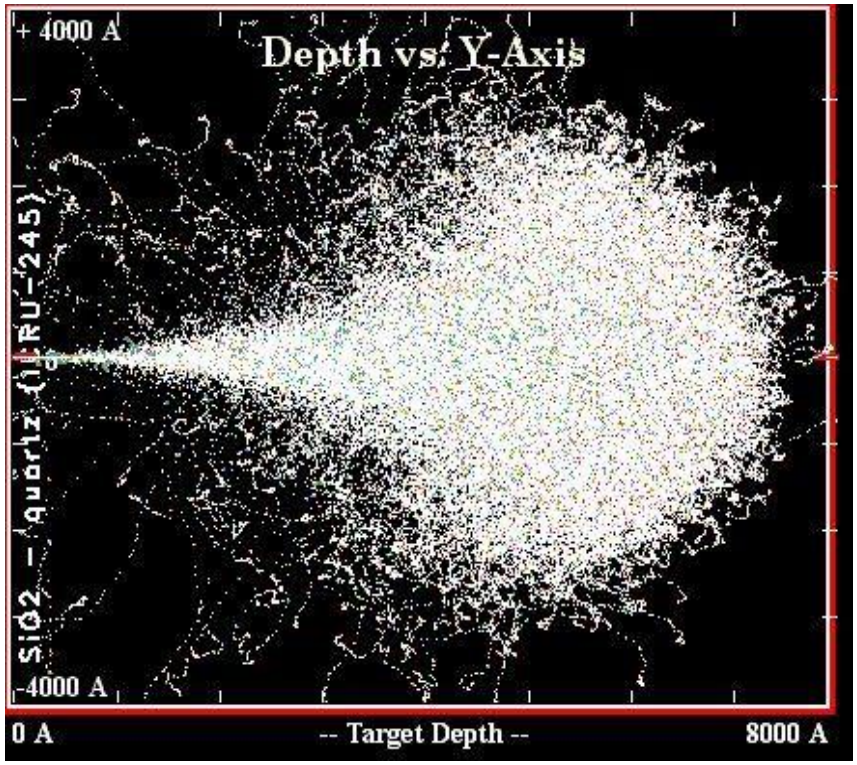


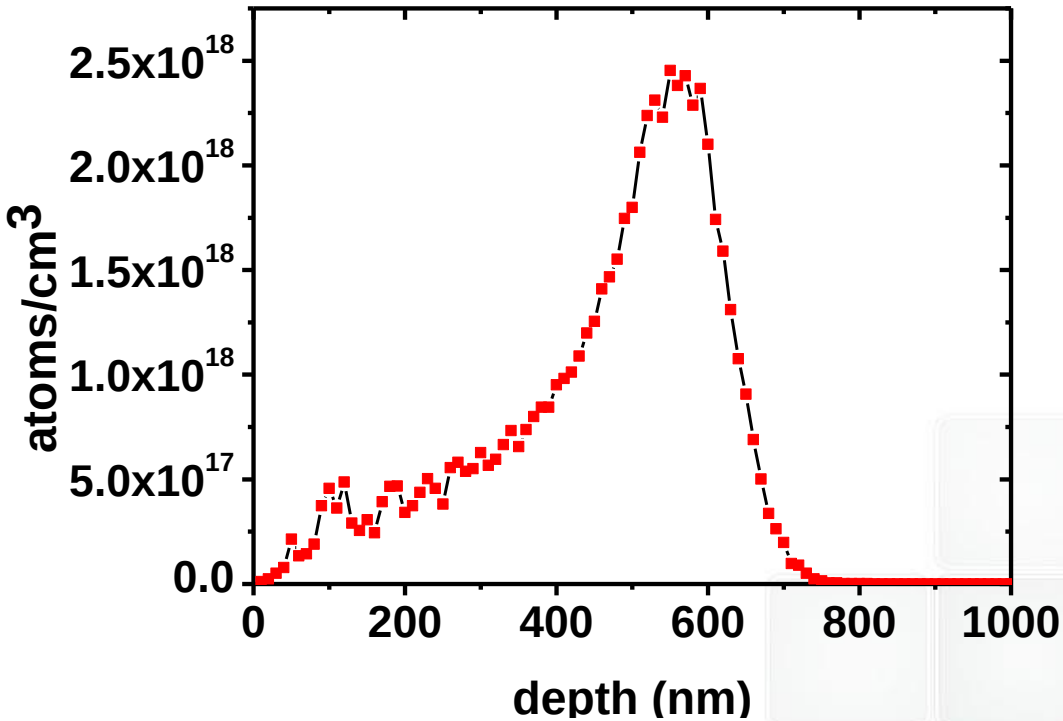
proton damage : 60 keV, fluence: 10^{13} p^+/cm^2

fused silica substrate

SRIM 2012 (The **S**topping and **R**ange of **I**ons in the **M**atter)

J. F. Ziegler and J.P.Biersack, www.srim.org





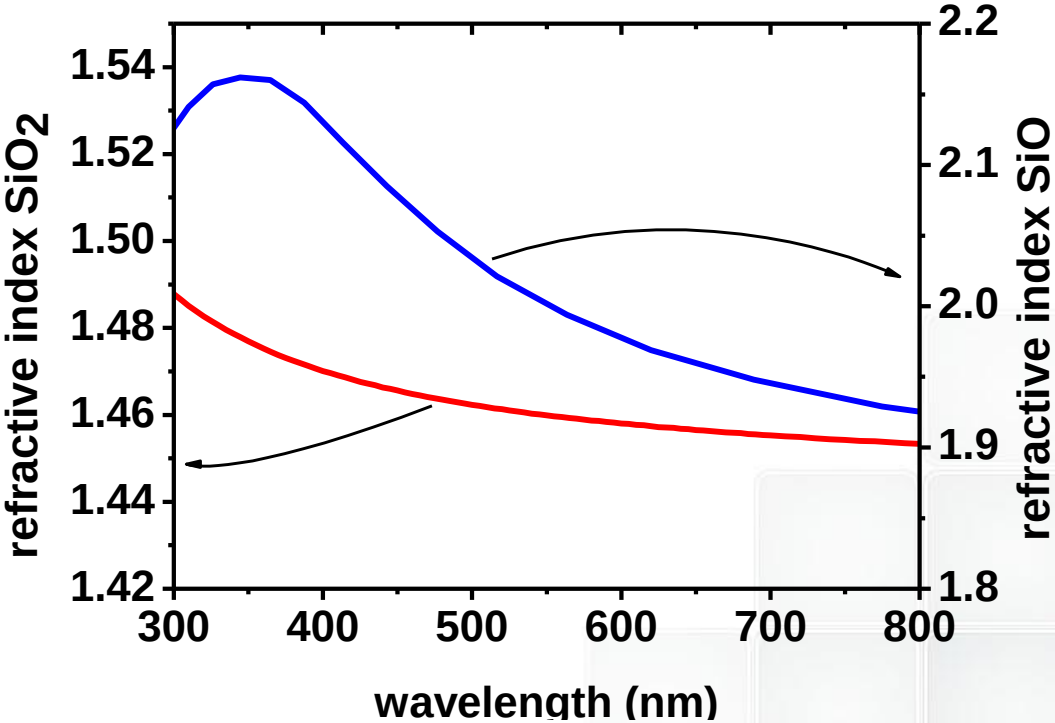
low refractive index layer, SiO_2

Hypothesis:

the low refractive index layers, SiO_2, subjected to protons irradiation, are responsible for the change in the transmittance curves.

Proton damage $Si{:}O_2 = Si{:}O + O$

the low refractive index layers can be considered a mixing of SiO_2 and SiO after the proton irradiation



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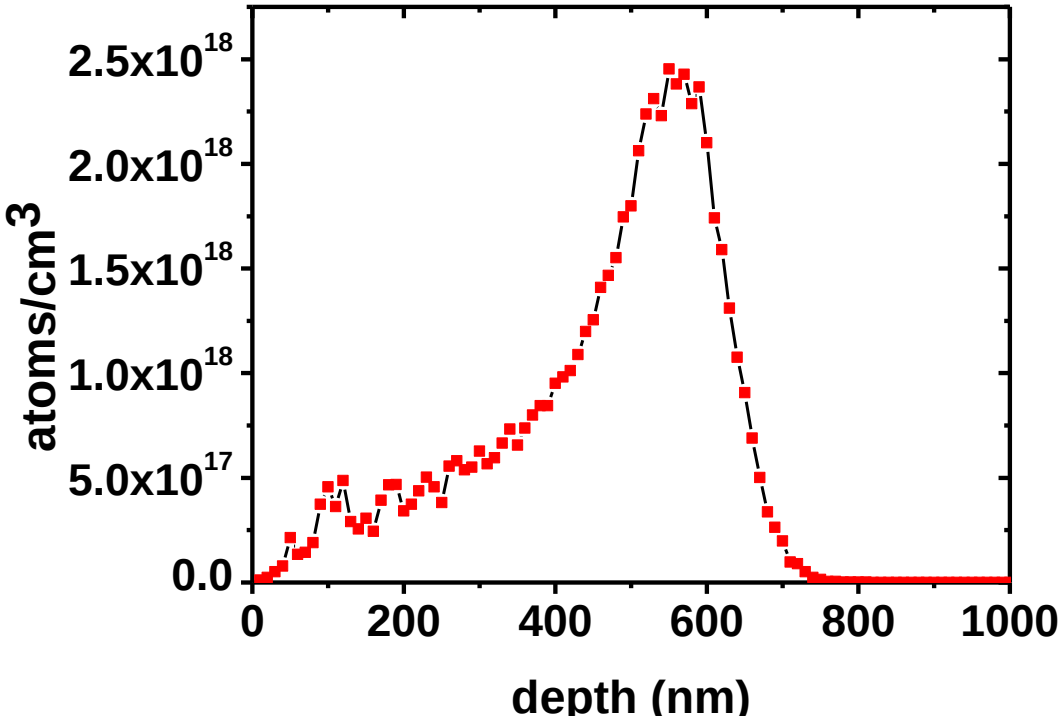
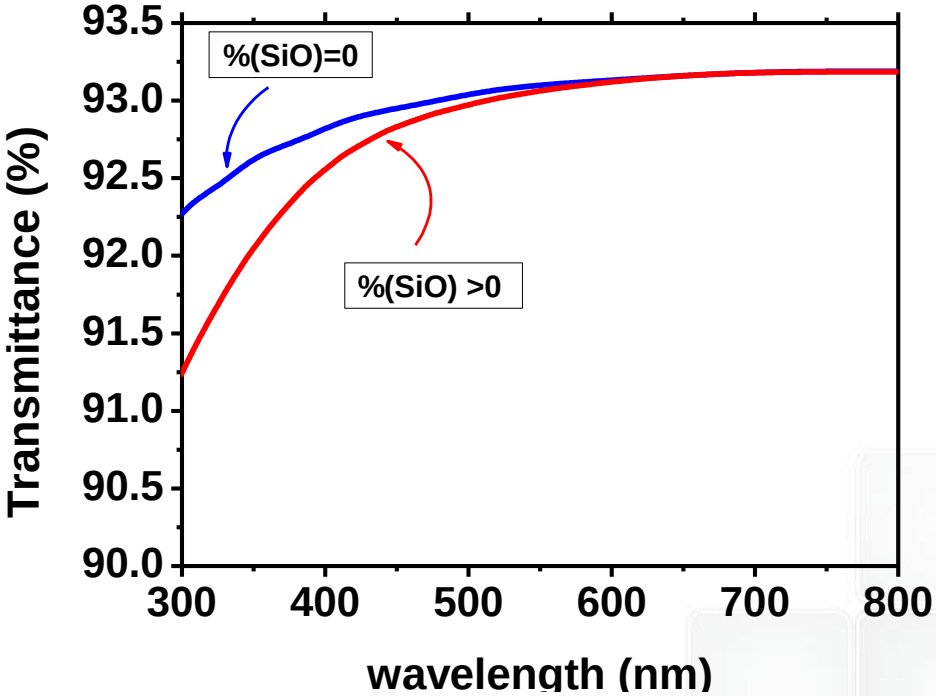
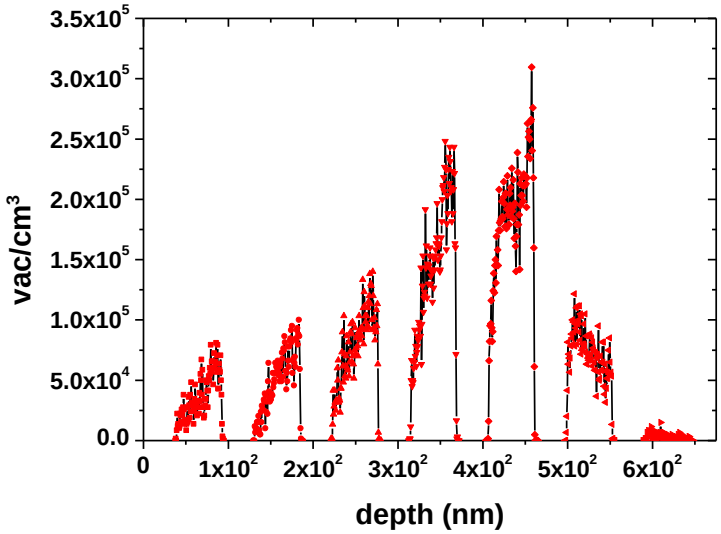




$Si{:}O_2 = Si{:}O + O$

proton damage : 60 keV, fluence: 10^{13} p^+/cm^2



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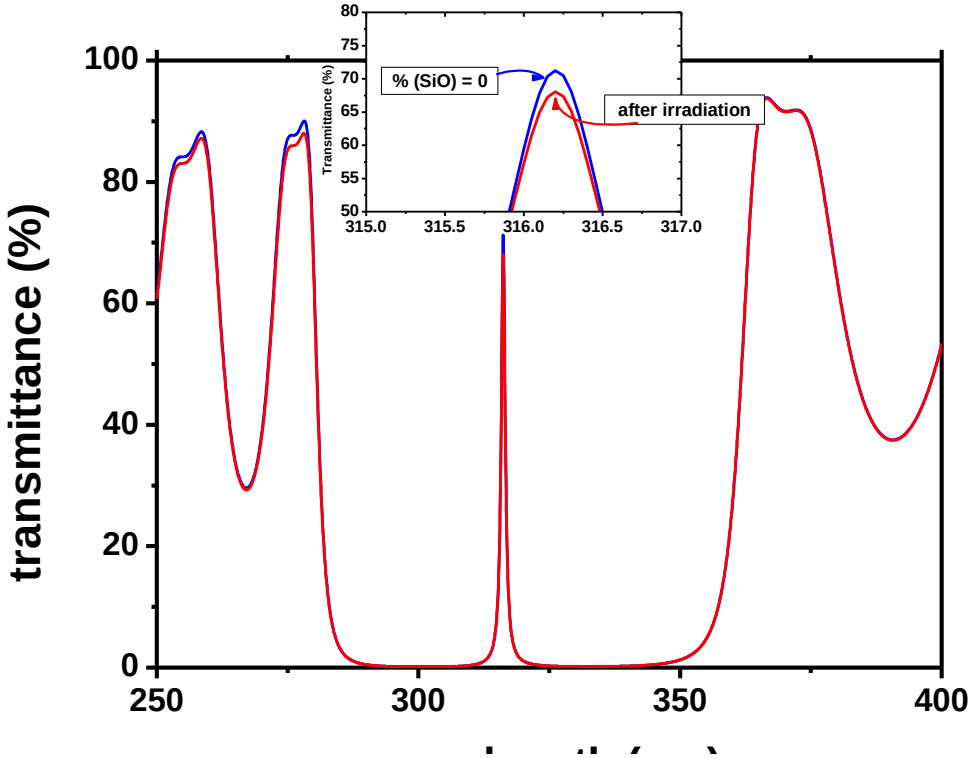
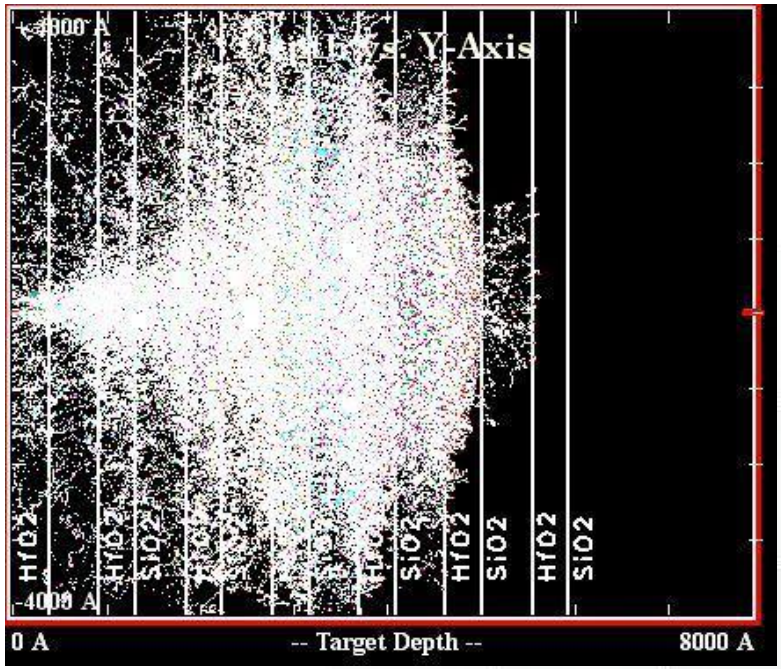
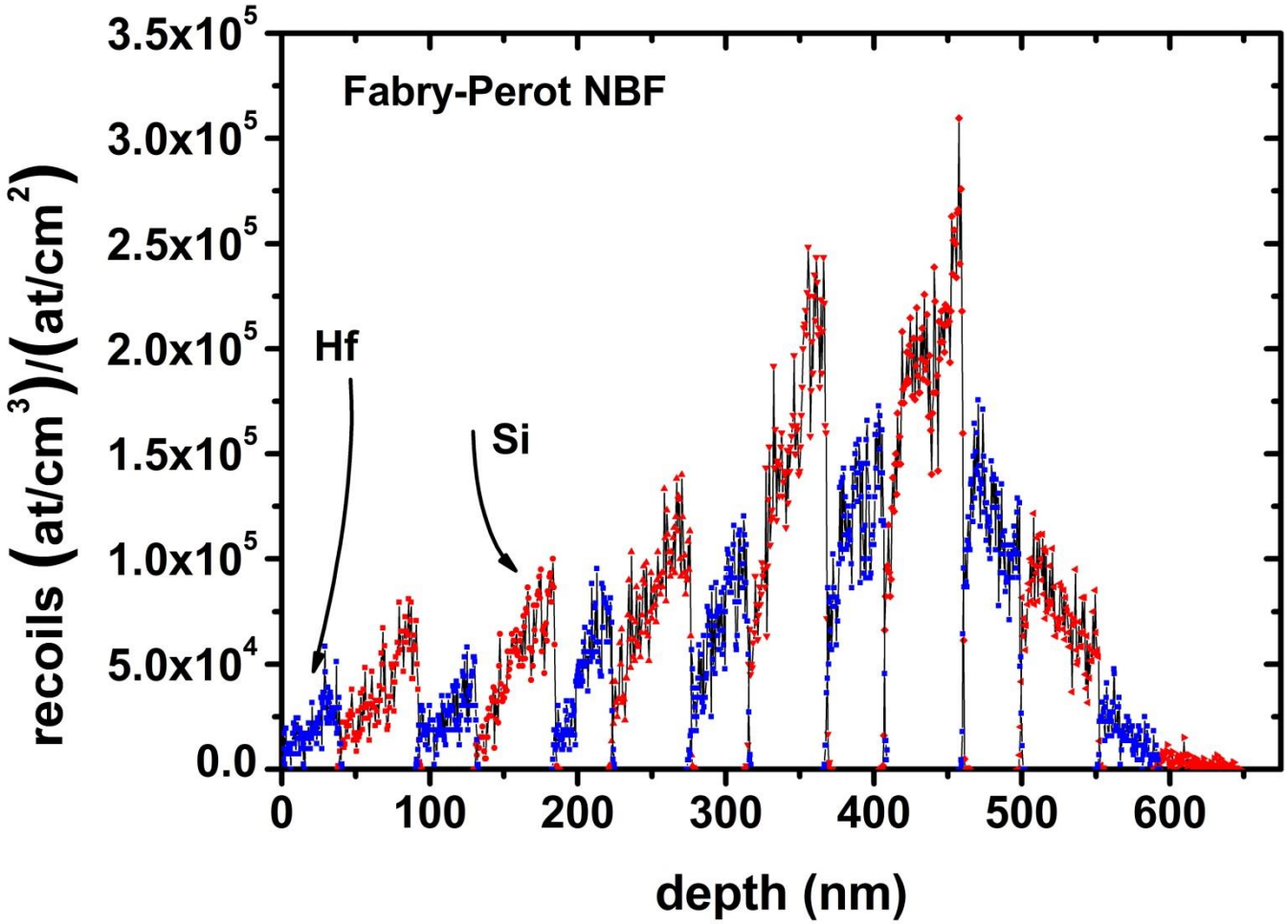
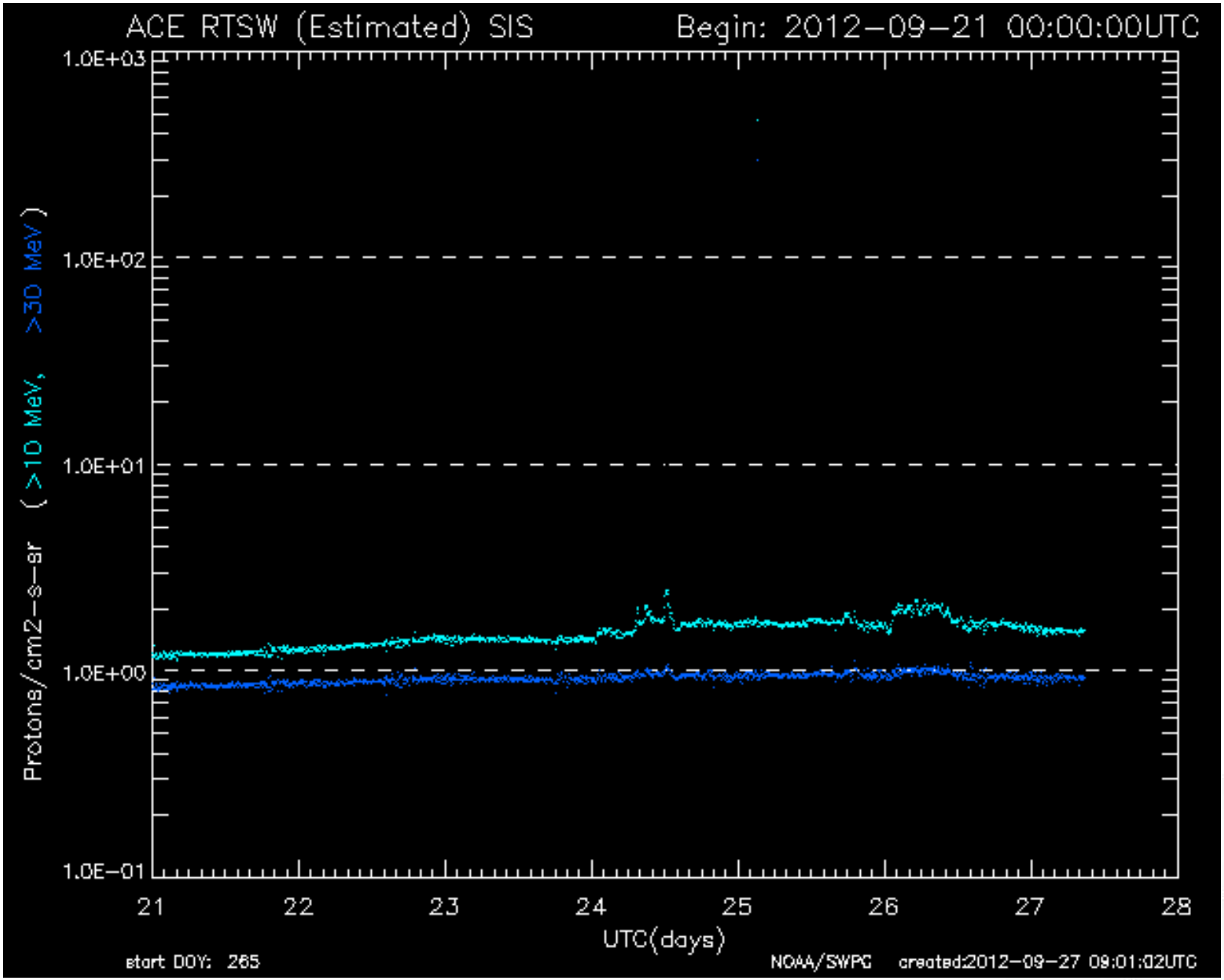




SiO_2/HfO_2 SRIM simulation

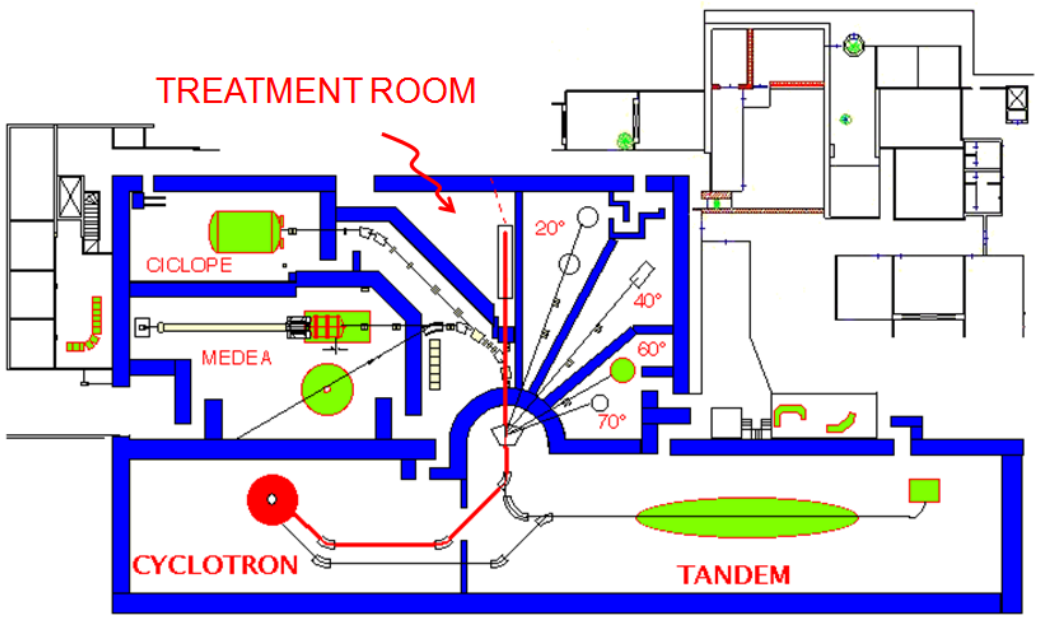


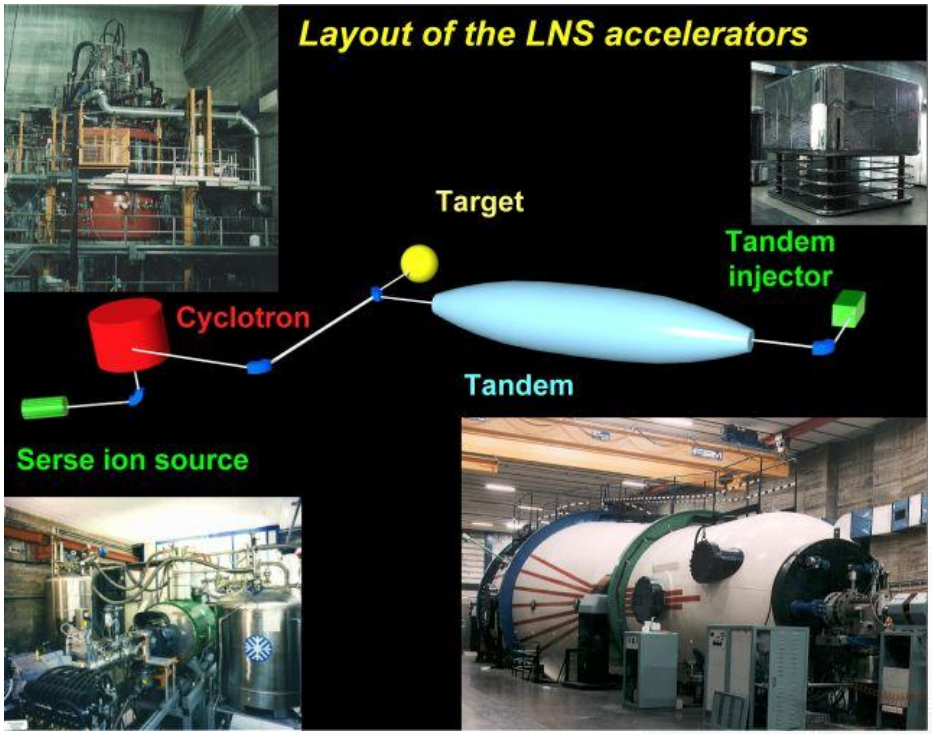
Space radiation: high energy protons 30 MeV



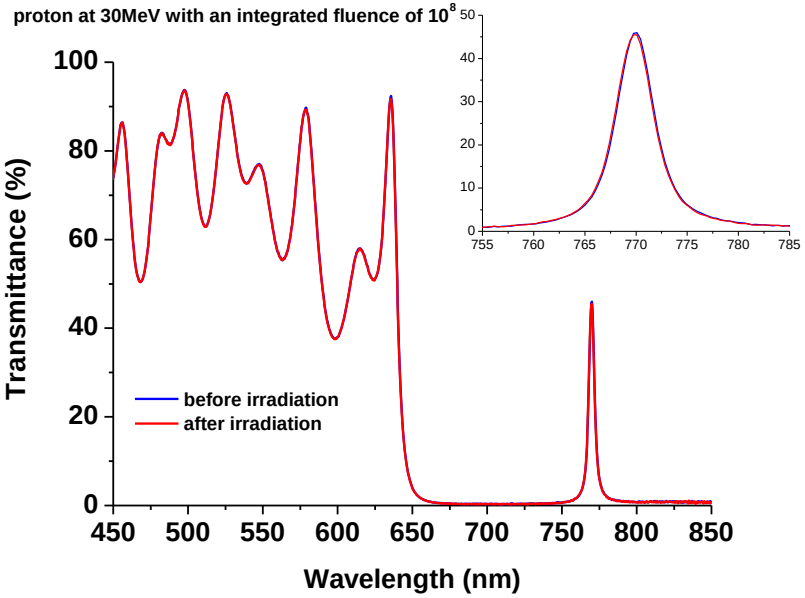
high energy protons : 30 MeV, fluence: 10^8 p^+/cm^2

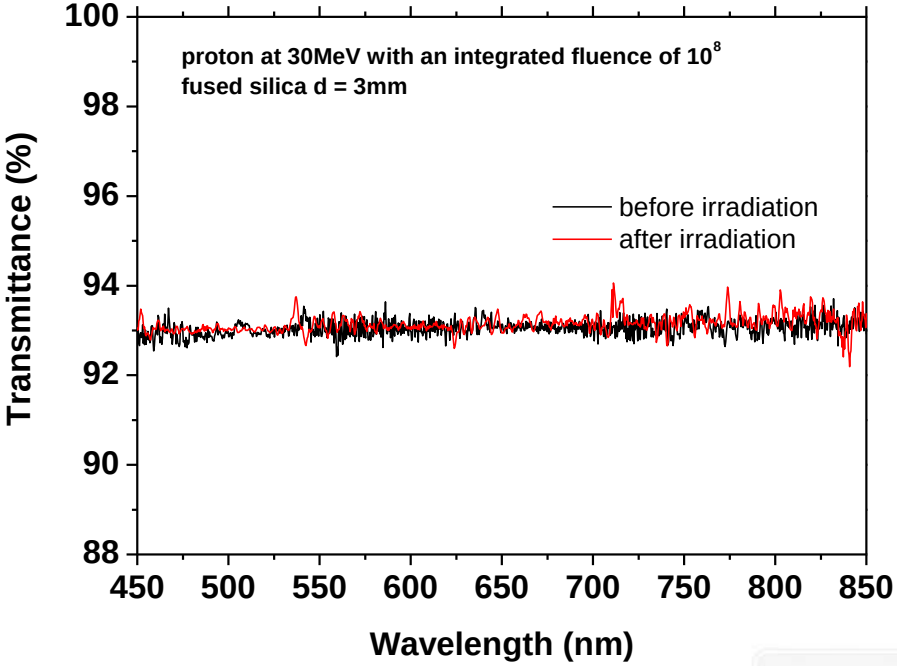
INFN-LNS (National Institute of Nuclear Physics, National South Laboratory, Italy)

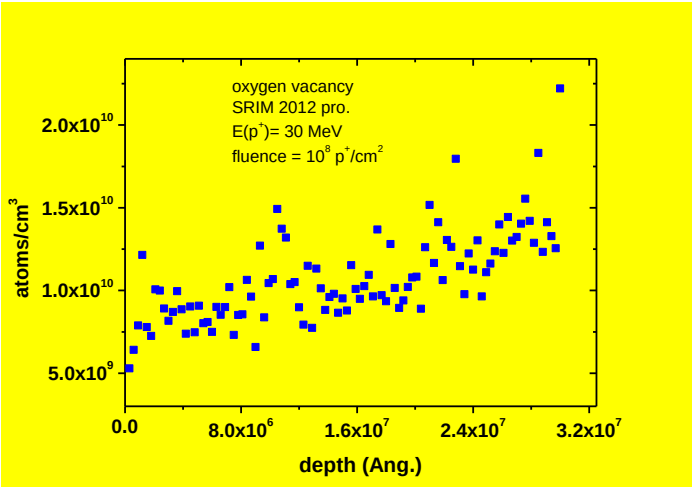




high energy protons : 30 MeV, fluence: 10^8 p^+/cm^2

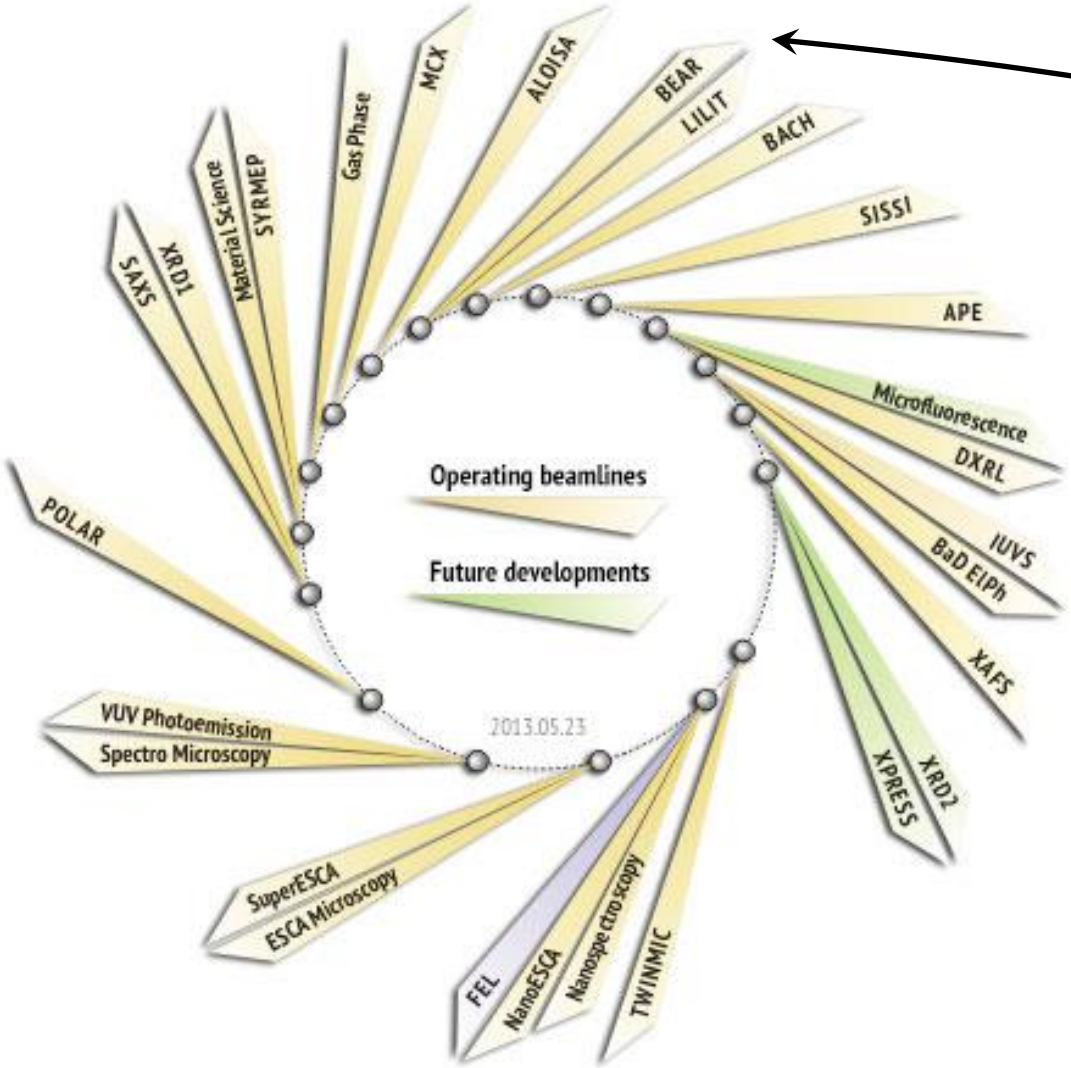


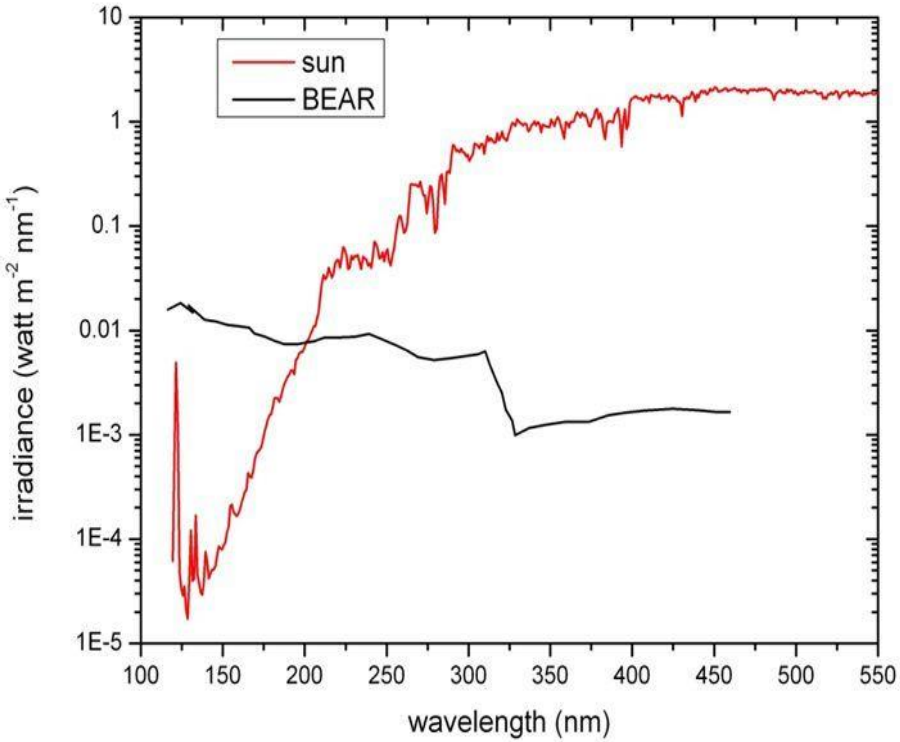




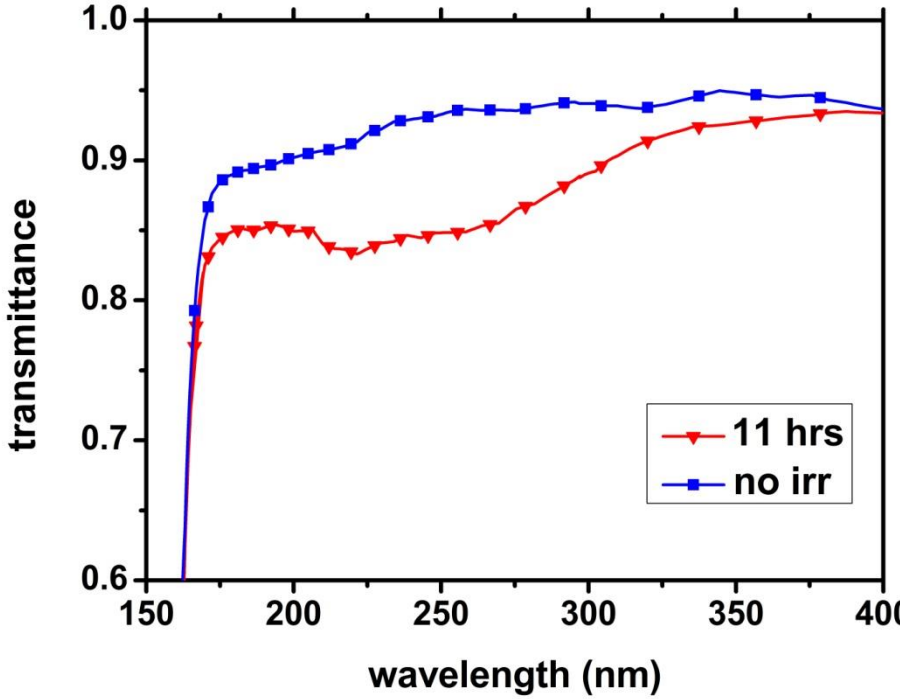
Trieste – Elettra, BEAR

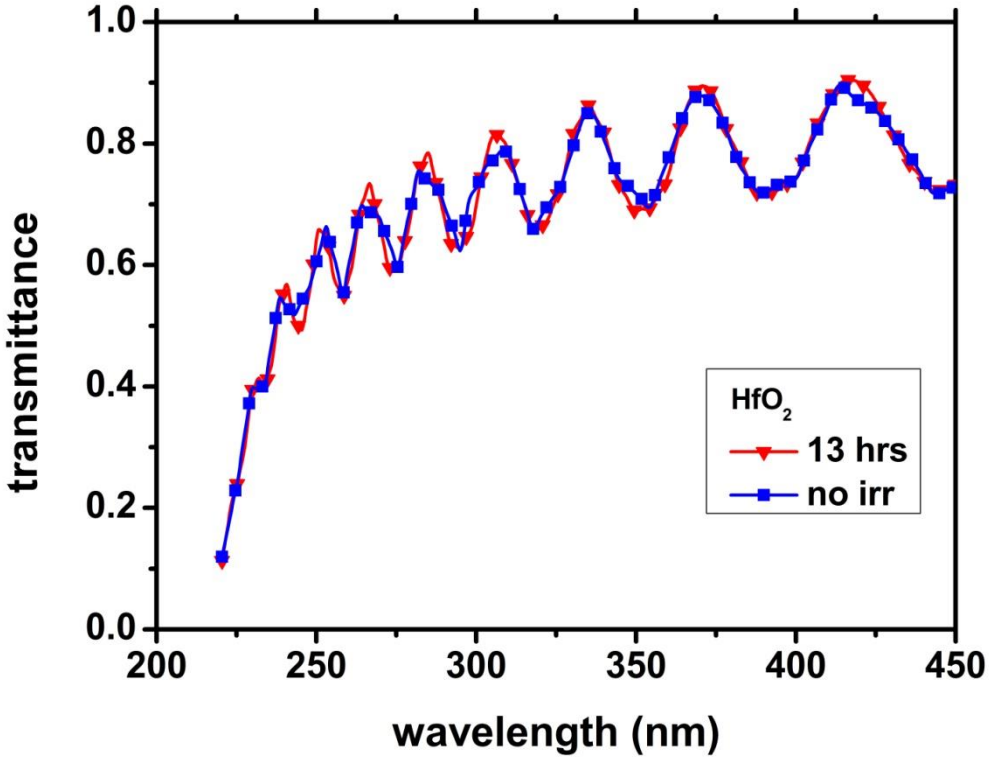
Bending magnet for Emission, Absorption and Reflectivity beamline



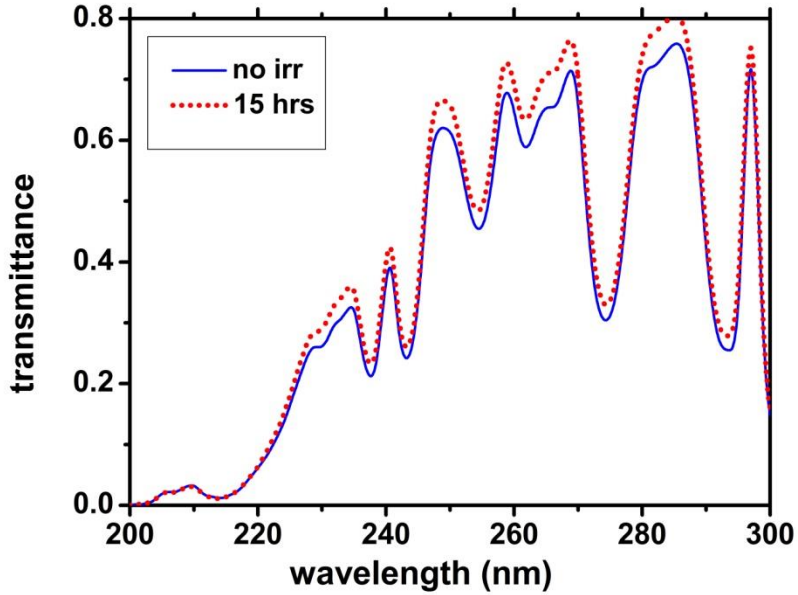


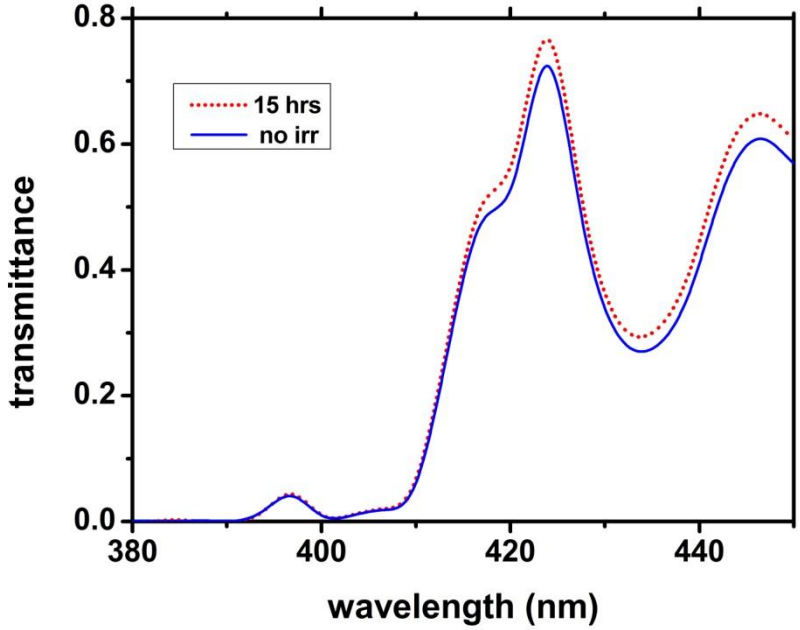
UV irradiation

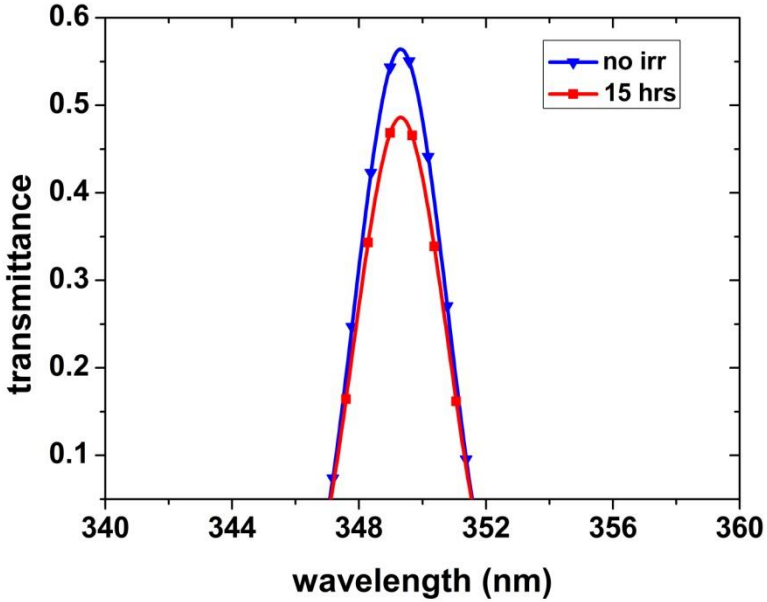




UV irradiation



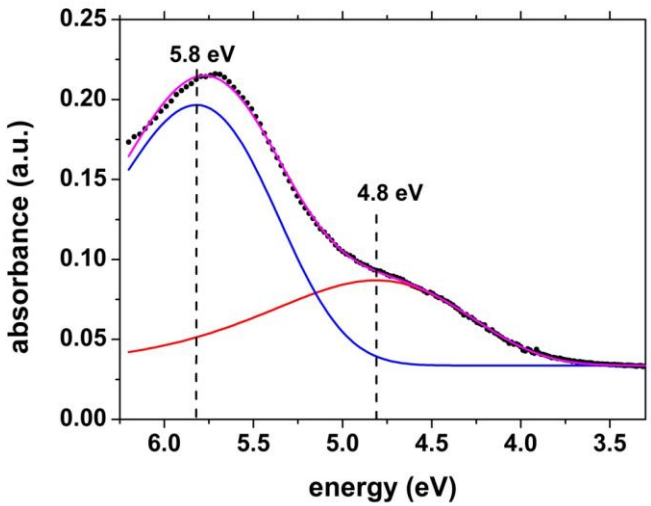




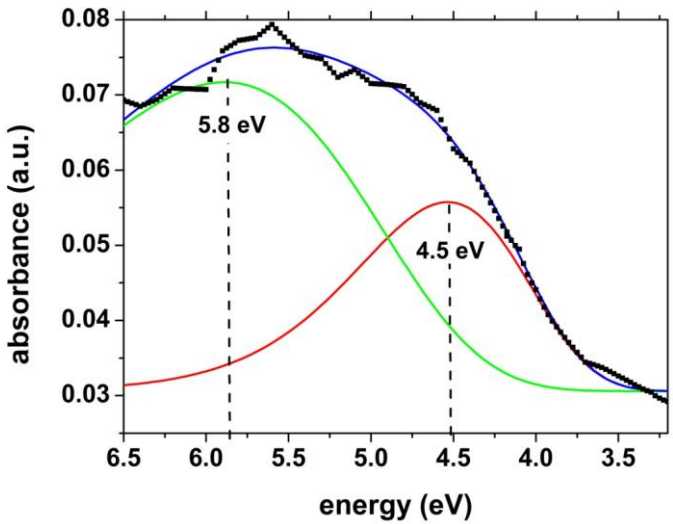
SiO_2 E' color center formation

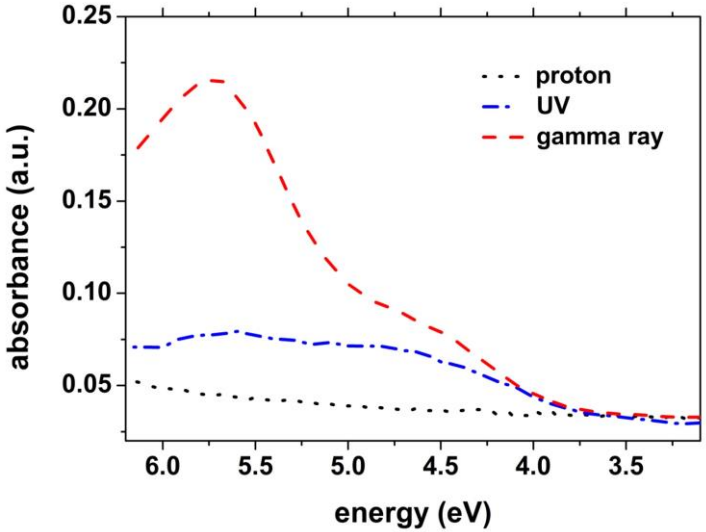
The **E'-center** is stable and is related to Oxygen vacancy with an electron trapped in the 3p orbital of Si-Si bond.

γ - rays



UV radiation





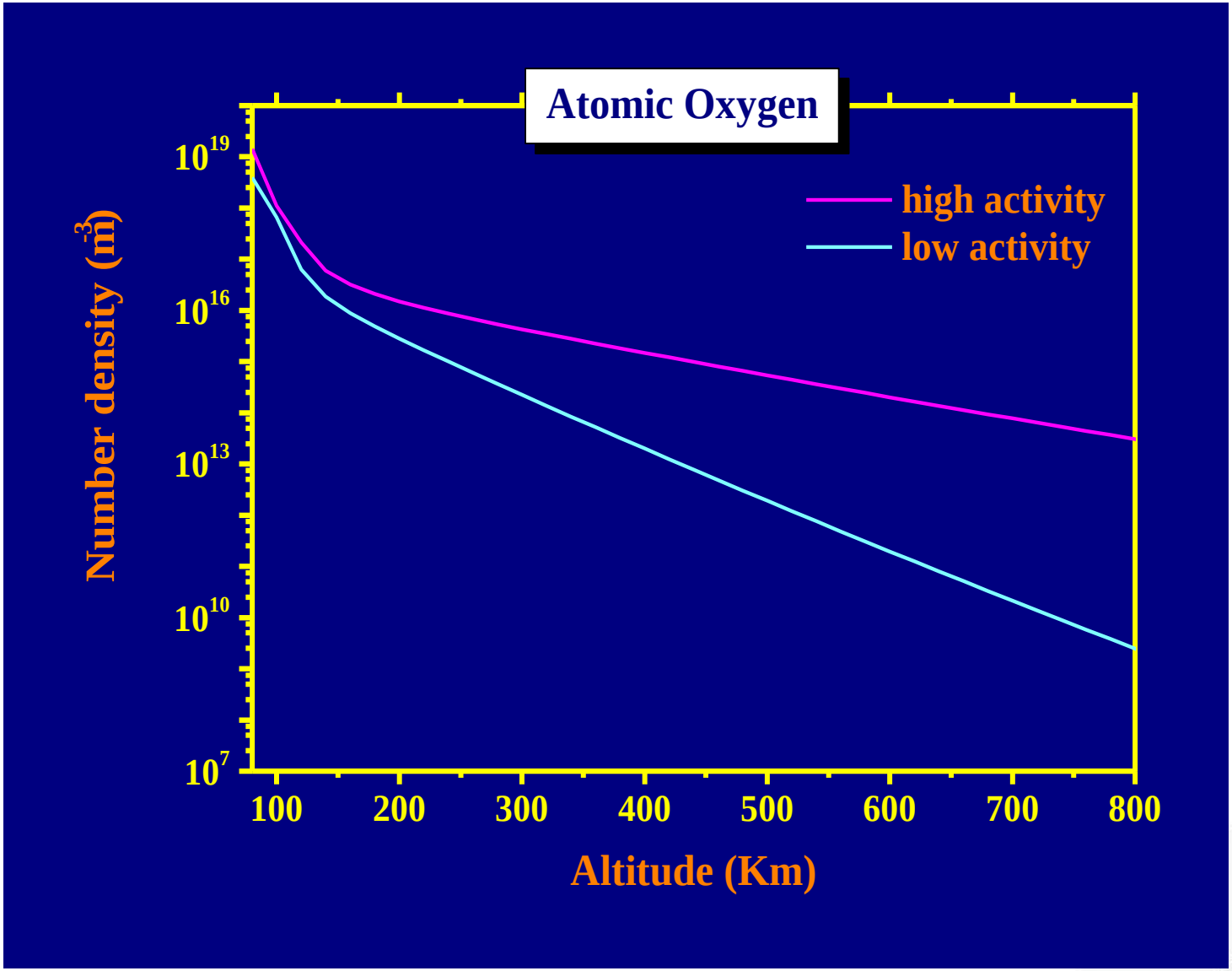
Low Earth Orbit (200 – 600 Km)

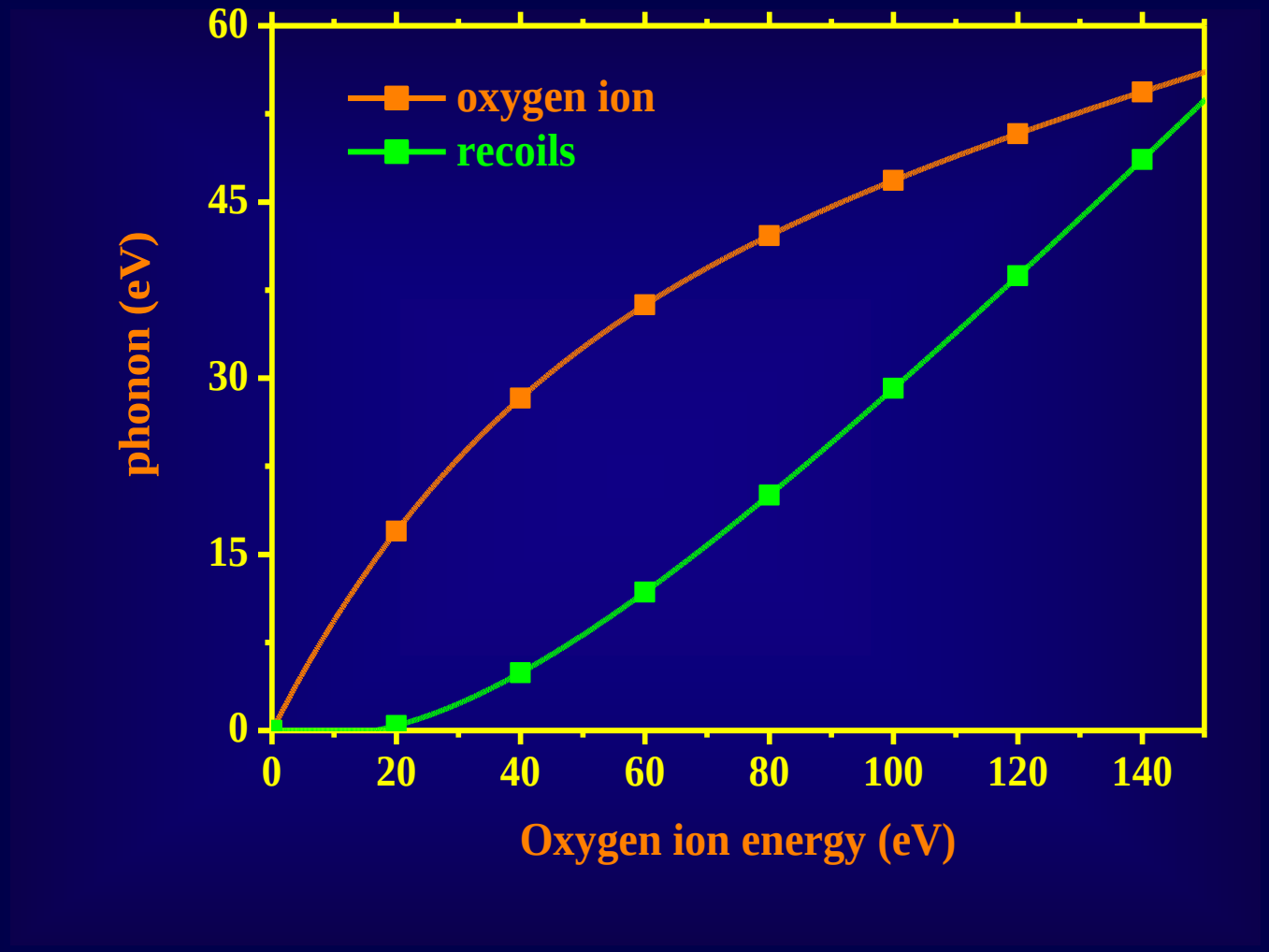
Neutral Atmosphere Constituents

80% Atomic Oxygen O

20% O_2 N_2 Ar He H

AO energy = 5-7 eV




oxygen ion
recoils
phonon (eV)
Oxygen ion energy (eV)
0
15
30
45
60
0
20
40
60
80
100
120
140

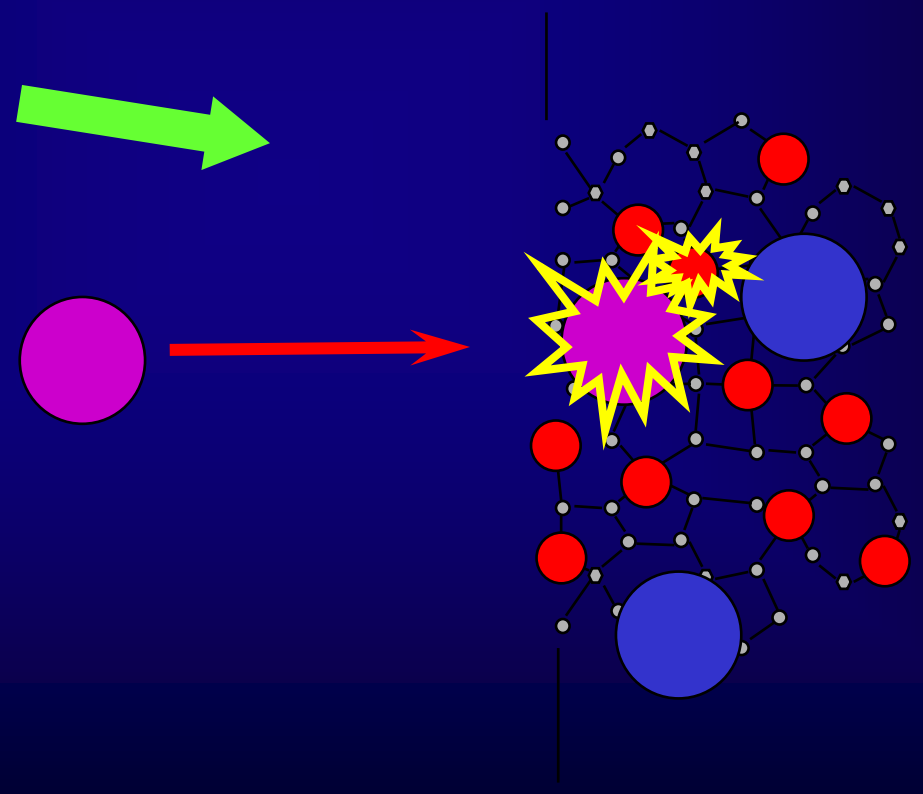
Finally, if E1<Ed and E2<Ed, then Z1 becomes an ***interstitial*** and E1+E2 is released as ***phonons***. If a target has several different elements in it, and each has a different displacement energy, then Ed will change for each atom of the cascade hitting different target atoms.

interstitial

$E_1<E_d$

$E_2<E_d$

E_1+E_2 (fononi)



Spherical thermal spike

Transport equation

$$J_E = -D\, grad \rho_E$$

Conservation of energy

$$\frac{\partial \rho_E}{\partial t} + div J_E = 0$$

$$\frac{\partial \rho_E}{\partial t} = D \nabla^2 \rho_E$$

J_E *: flux of energy at the sphere surface*

D *:costante of diffusion*

$$T_S(r,t) = \frac{E_{ph}}{8\pi^{\frac{3}{2}} cd\ (Dt)^{\frac{3}{2}}} \frac{1}{} e^{\frac{-r^2}{4Dt}}$$

$$T_{cyl}(\rho,t) = \frac{E_C}{4\pi cdDt} e^{\frac{-\rho^2}{4Dt}}$$

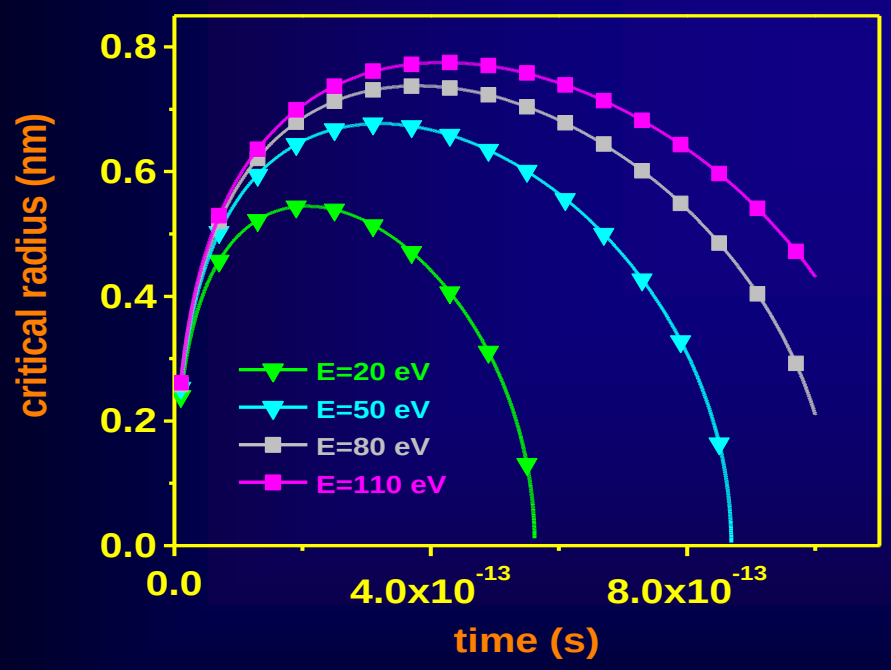
D = diffusion coefficient
E = phonon energy
r = distance from the place where the phonons are generated
t = time

Table I: physical constant of Kapton material.

c (specific heat)	1090	$\frac{J}{Kg\,K}$
d (mass density	1.42	$\frac{Kg}{m^3}$
D (diffusion coeff.)	$2.39 \cdot 10^{-7}$	$\frac{m^2}{\sec}$
T_C (critical temperature)	800	K

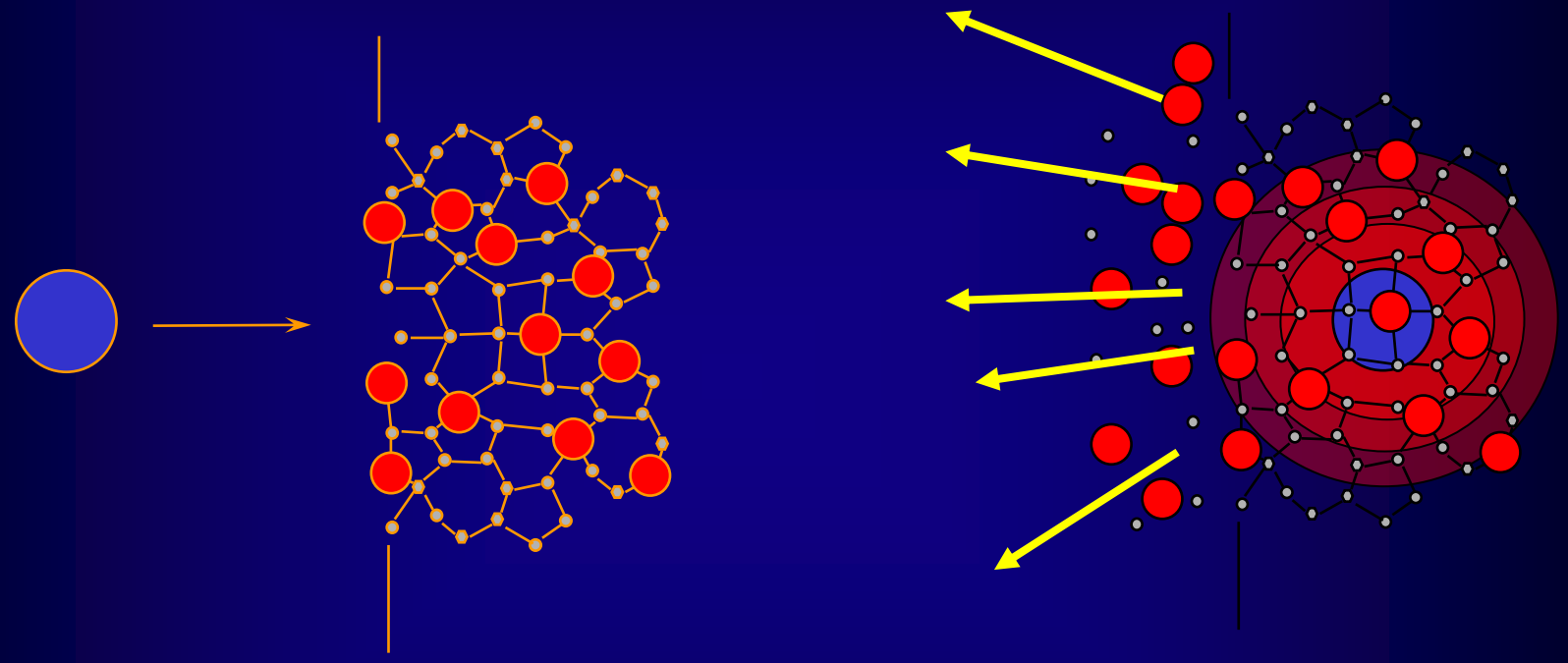
A critical spike volume can be defined as the volume in which the atoms posses a high probability of being involved in a rearrangement process. In this volume, the temperature is higher than the melting temperature T_C of the material

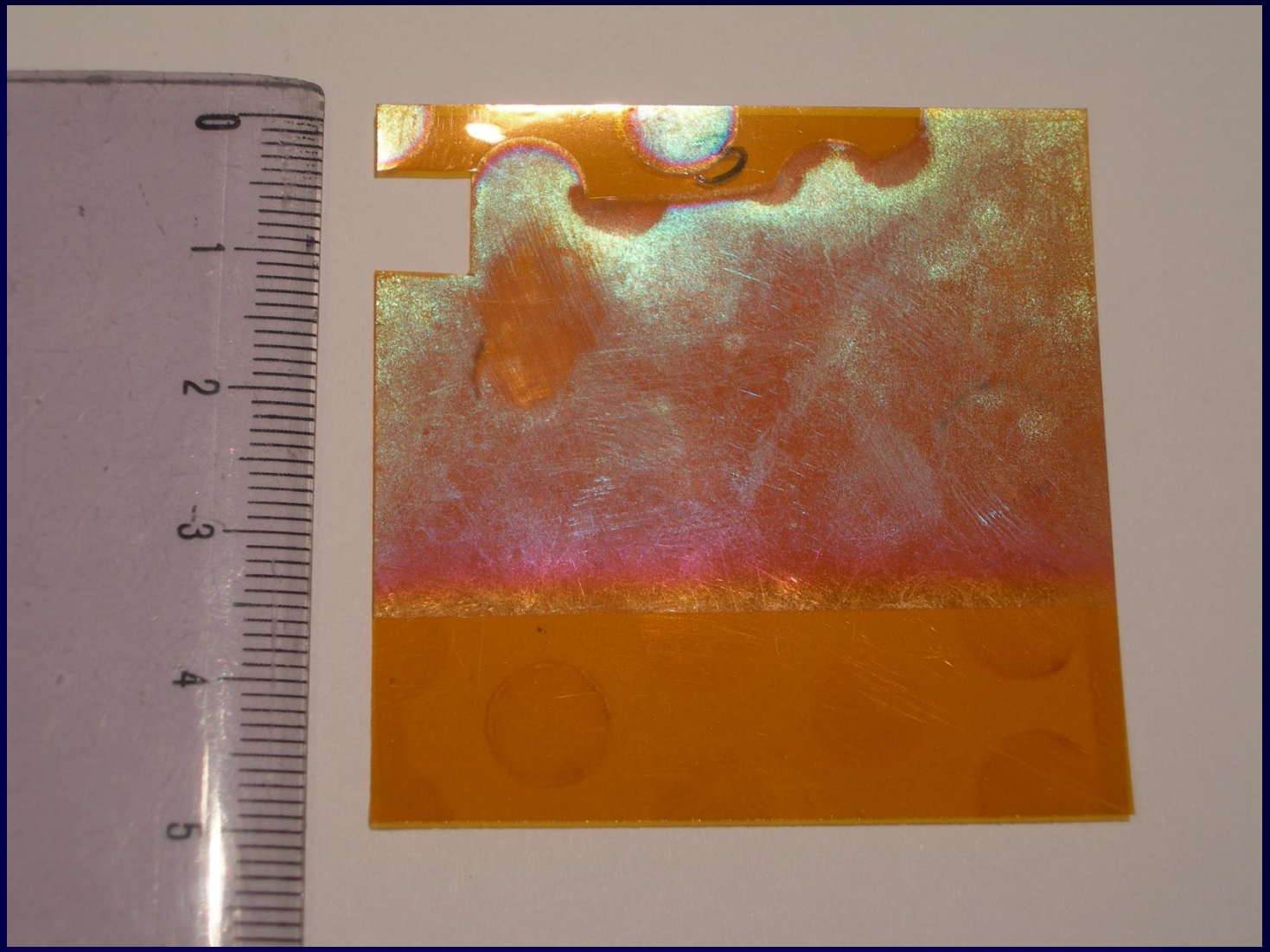
$$r_C(t, E_{oxy}) = 2 \cdot \left(-\ln\left(4.5 \cdot 10^{-8} \cdot \pi^{\frac{3}{2}} \cdot T_C \; cd \cdot t \, \frac{(D \cdot t)^{\frac{1}{2}}}{E_{ph}(E_{oxy})} \right) \cdot D\, t \right)^{\frac{1}{2}}$$



$$\frac{\partial r_c(E_{oxy}, t)}{\partial t} = 0$$

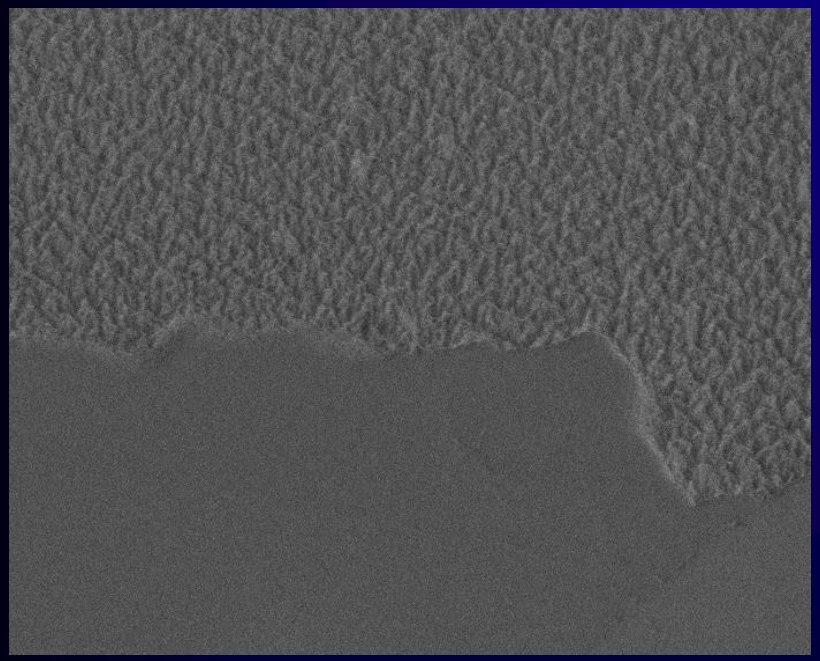
$$V_{melt}(E_{oxy}) = \frac{4}{3} \cdot \pi \cdot r_{\max}(E_{oxy})^3 \qquad \left[nm^3 \right]$$

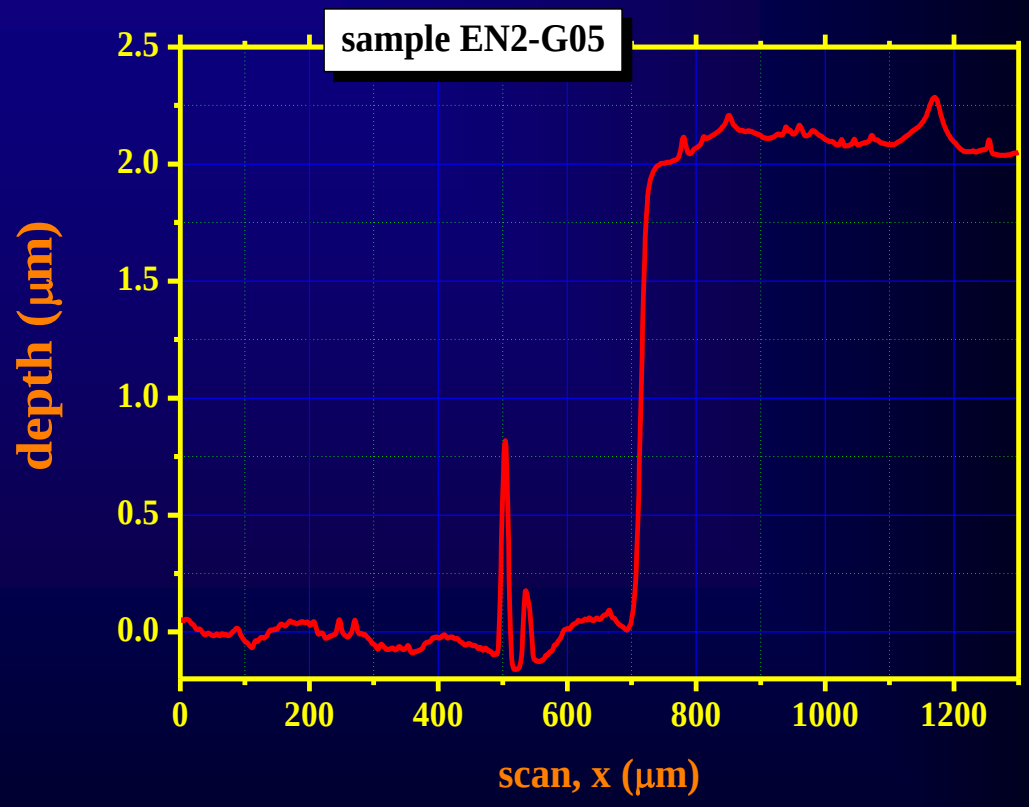



0
1
2
3
4
5

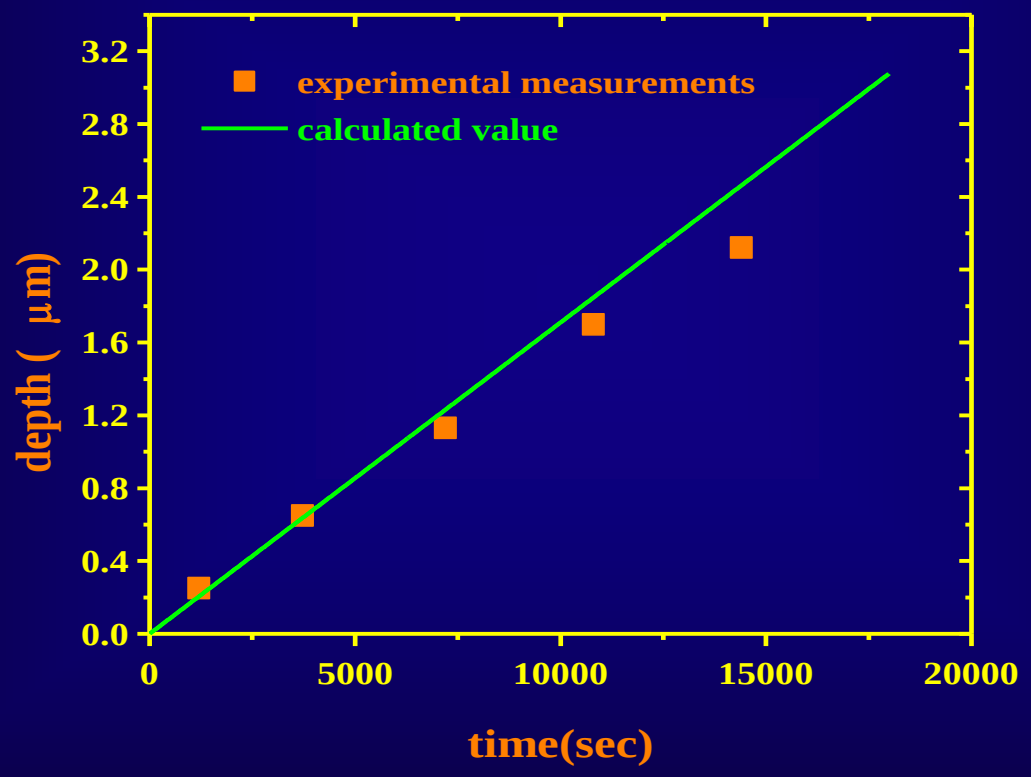
Measurement of step

by a surface pro-filometer (model P8 , manufactured by Ten-cor Instruments)





$$d(t) = t \cdot \int_{0}^{E_{\max}} \frac{n_K(E_{oxy})}{\rho_K \cdot 10^{-4}} dE_{oxy}$$



[cm^3/at]	Kapton	Aluminium	Glass
literature	$2\text{-}3.5 \times 10^{-24}$	2.29×10^{-27}	$0.4\text{-}2.3 \times 10^{-28}$
Spherical thermal spike	3.3×10^{-23}	4.5×10^{-25}	2.4×10^{-26}