Work on hadron effects on crystals for CMS at sLHC

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CMS SLHC workshop, Fermilab, October 29, 2009

ETH Institute for Particle Physics

Thorough reports regularly presented in ECAL meetings, including the November 2008 and March 2009 SLHC meetings. Update here:

- I - Studies of $PbWO_4$, CeF_3 and LYSO under hadron irradiation

→ New results on CeF_3 and LYSO

- II - Procurement and hadron irradiation of crystals for Beam Tests

→ 5 PWMO crystals purchased for test beam matrix

→ 1 $PbWO_4$ EE crystal p-irradiated in June'09 up to $\phi_p = 1x10^{13}$ p/cm^2, delivered for beam test

→ 1 PWMO crystal p-irradiated beginning of October up to $\phi_p = 1x10^{14}$ p/cm^2, to be delivered in 2010

Hadron fluences at sLHC

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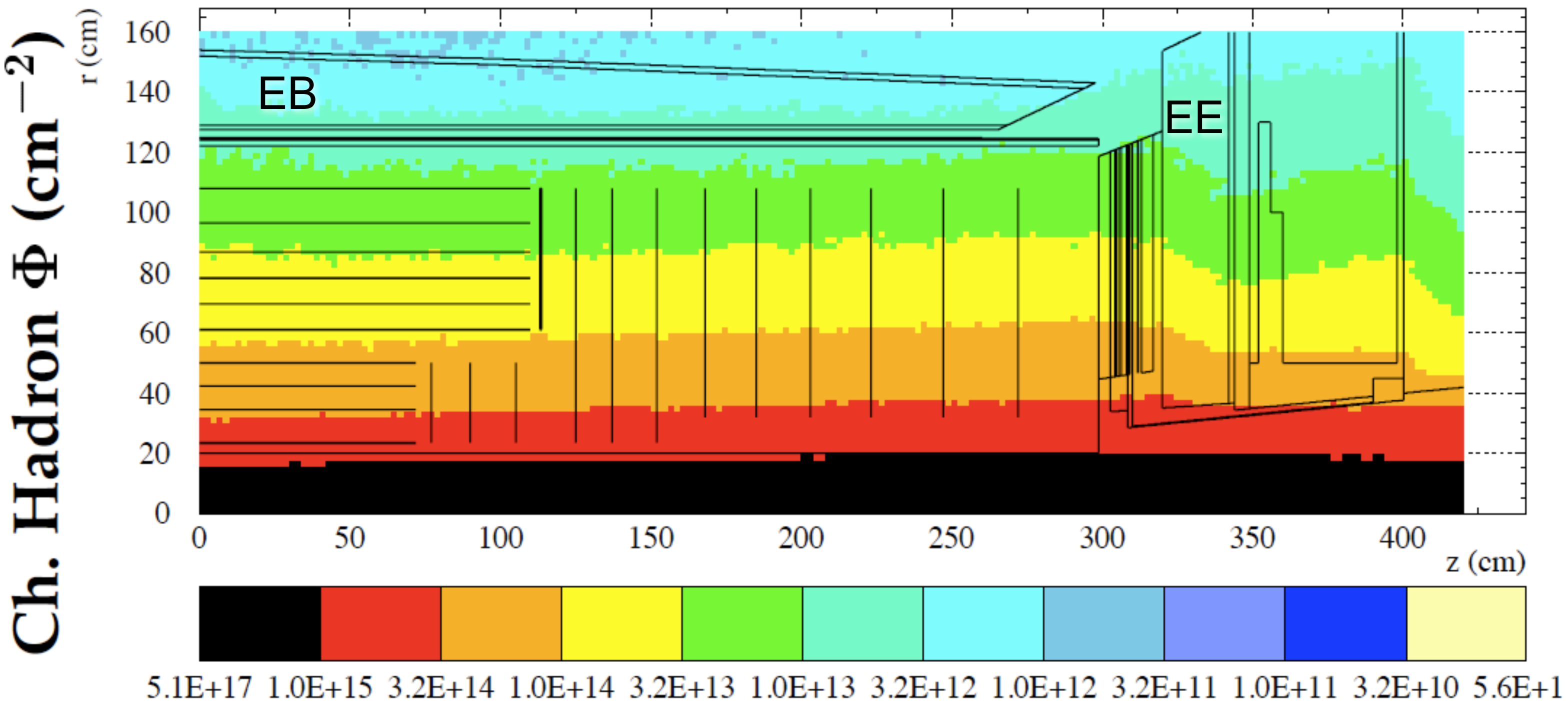
M.Huhtinen, sLHC electronics workshop 2004

Ionizing radiation doses and particle fluences [cm^{-2}] calculated for 2500 fb^{-1} in the CMS electromagnetic calorimeter, i.e. after running until ~2025:

- Barrel (EB) : ~10^{12} cm^{-2} charged hadrons
- End Caps (EE) : up to ~10^{14} cm^{-2} charged hadrons



Neutrons:

- Below 20 MeV, no effect besides ionizing dose, tested up to 10^{14} cm^{-2}

R. Chipaux et al. Proc. Mat Res. Soc. 358 (1994) 481

- Above 20 MeV, effects as for charged hadrons, parametrised by density of inelastic collisions

Reminder: hadron damage features in $PbWO_4$

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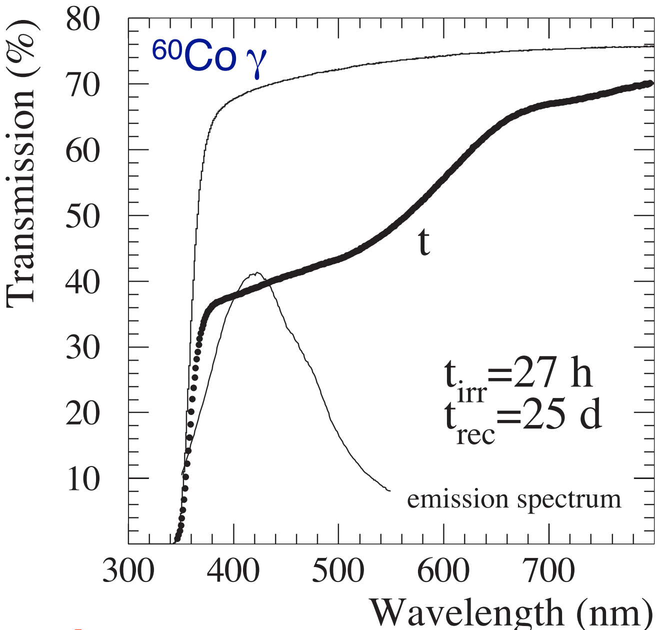

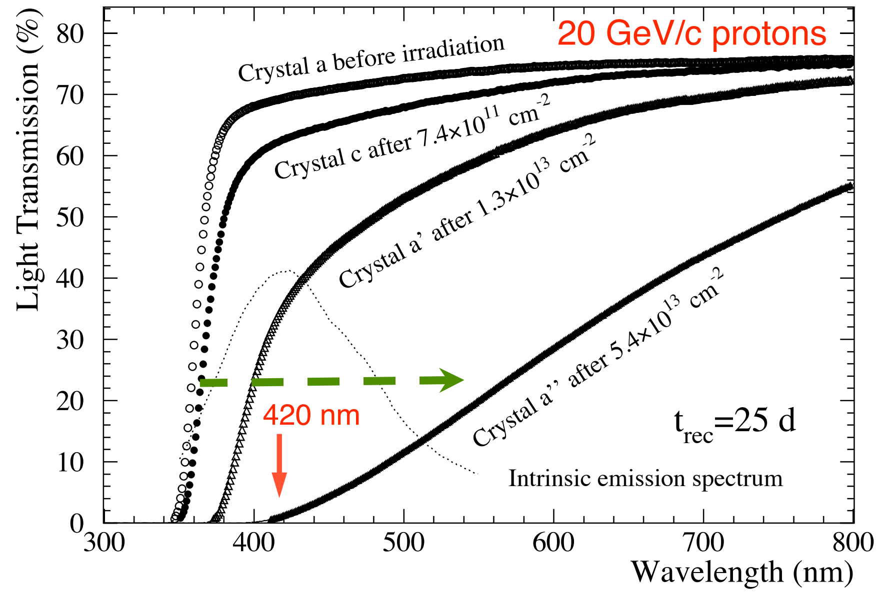

→ It induces changes in Light Transmission, qualitatively different from those caused by γ radiation

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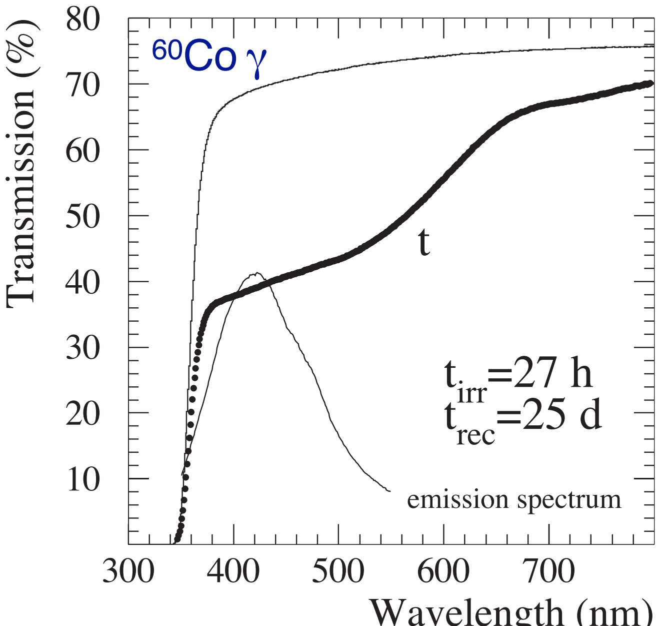
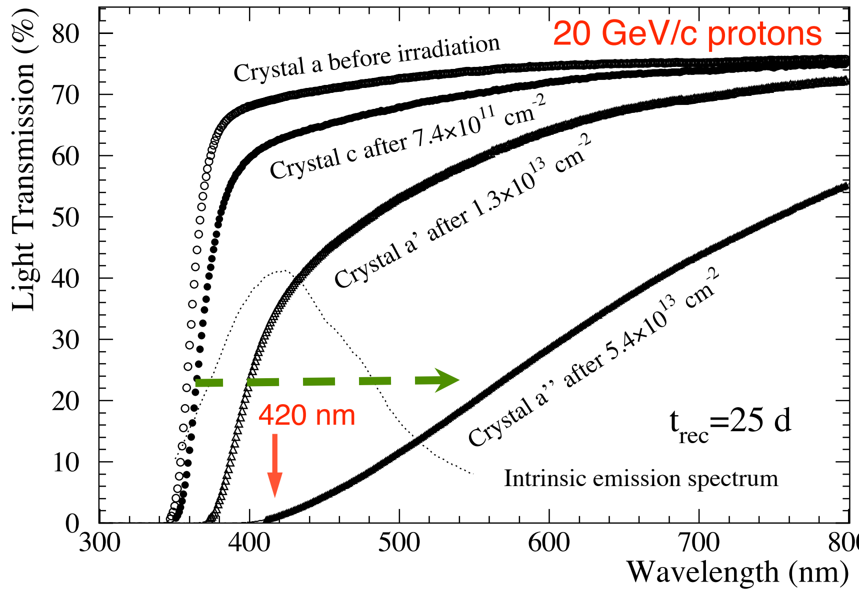
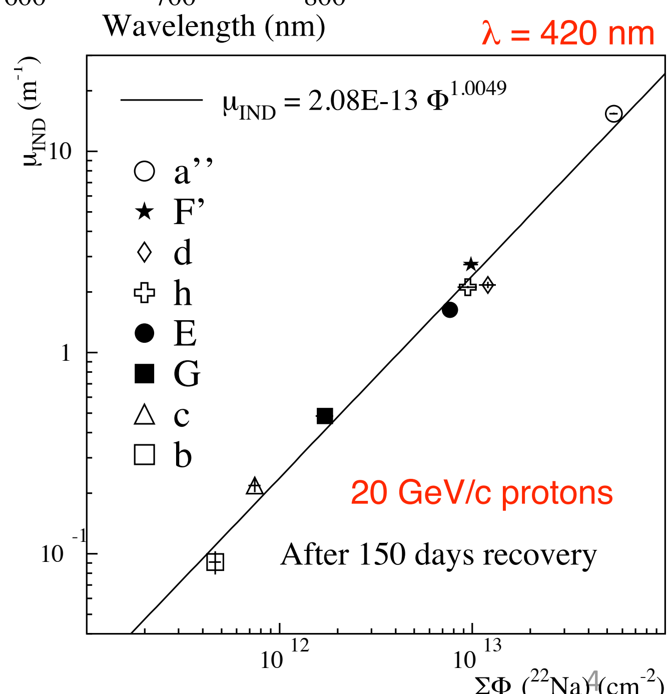




→ It induces changes in Light Transmission, qualitatively different from those caused by γ radiation

→ Tested over 2 orders of magnitude in proton fluence, up to 5×10^{13} /cm^2 and over a factor 20 in rates. The non-recovering component of μ_{IND} grows linearly with fluence

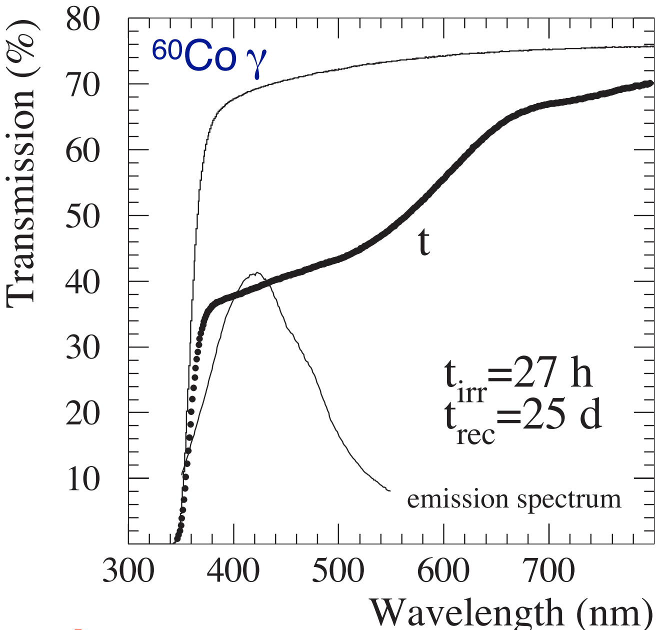
M. Huhtinen, P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, Nucl. Instr. Meth. A545 (2005) 63-87

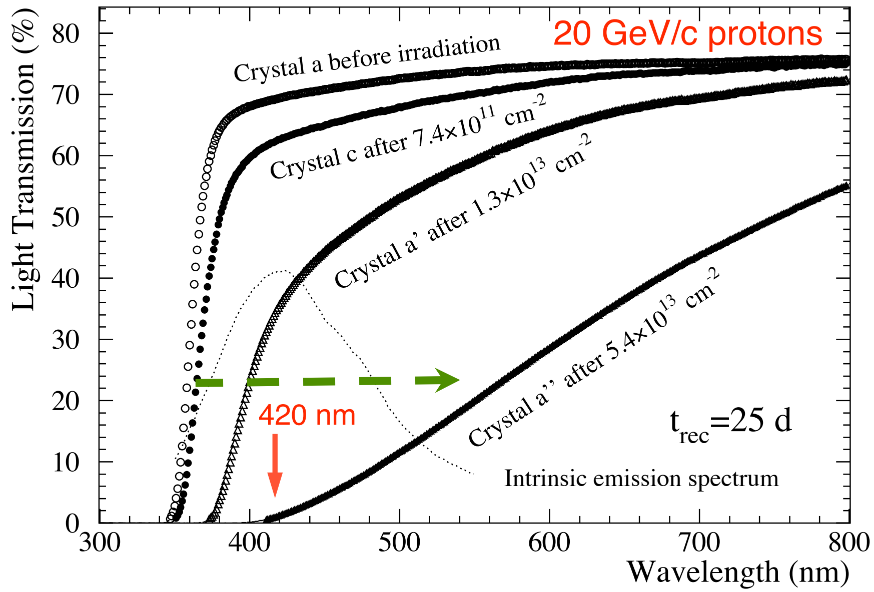


→ Parametrize through induced absorption:

$$\frac{LT(\lambda)}{LT_0(\lambda)} = e^{-\mu_{IND}(\lambda)L}$$

Reminder: hadron damage features in PbWO4





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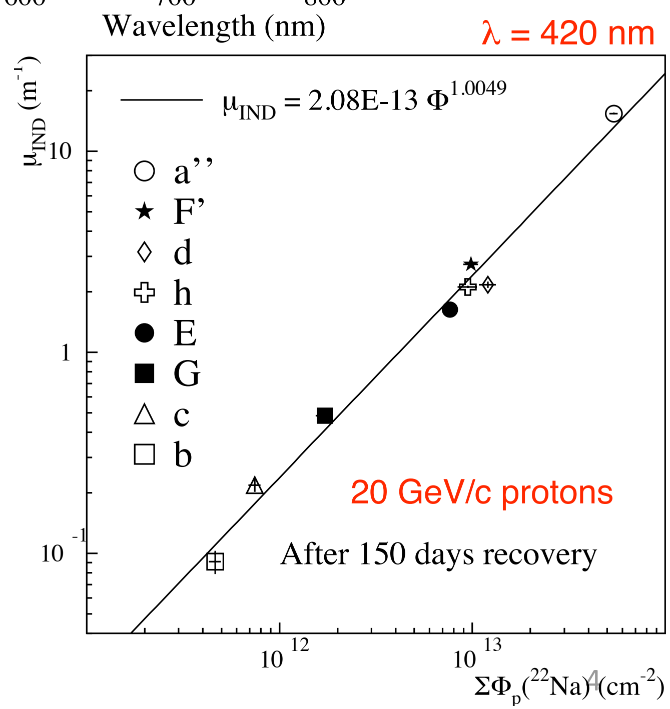

→ It only affects Light Transmission, and can thus be monitored

P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, Nucl. Instr. Meth. A564 (2006) 164-168

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Comments on damage recovery in $PbWO_4$ after p-irradiation

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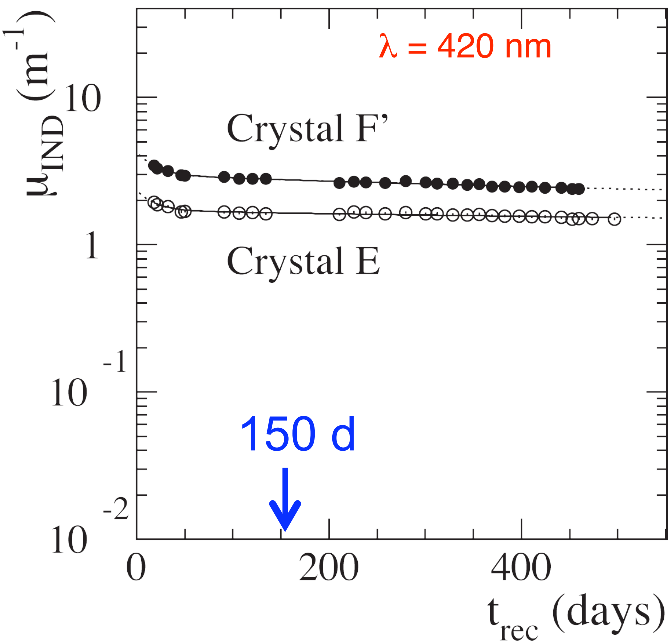

A fraction of the p-damage recovers in the dark, at room-T, with τ_1 = 17.2 days and τ_2 = 650 days as for γ-damage

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Damage at 150 days ~ stable

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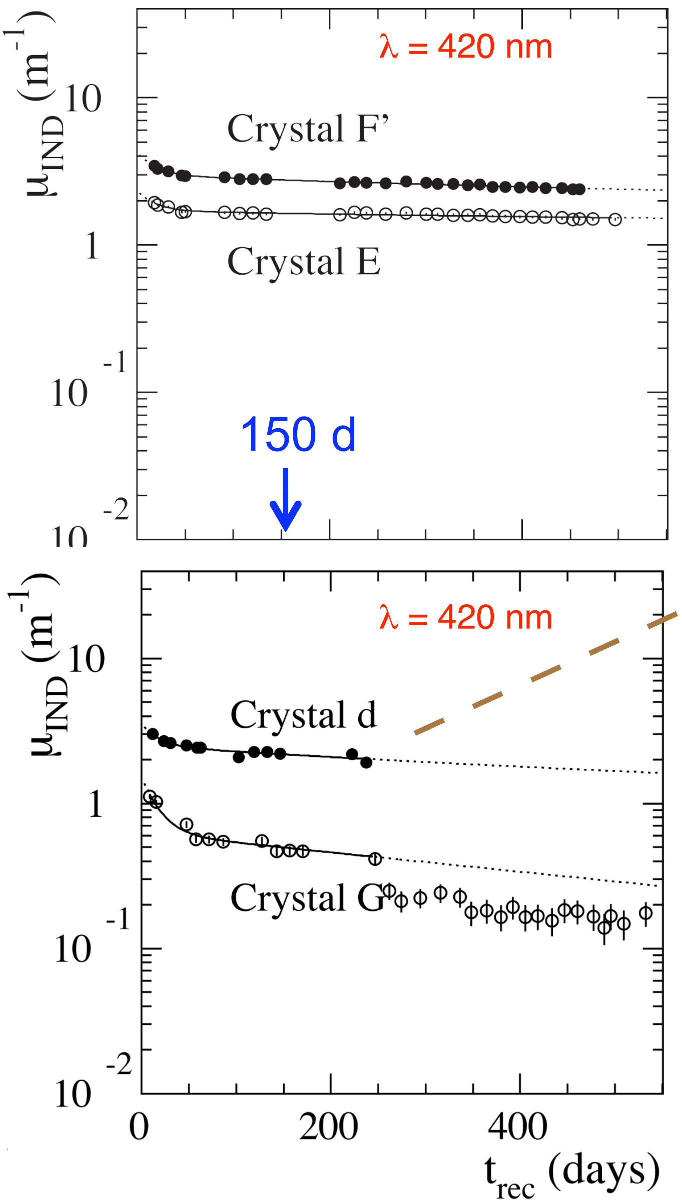

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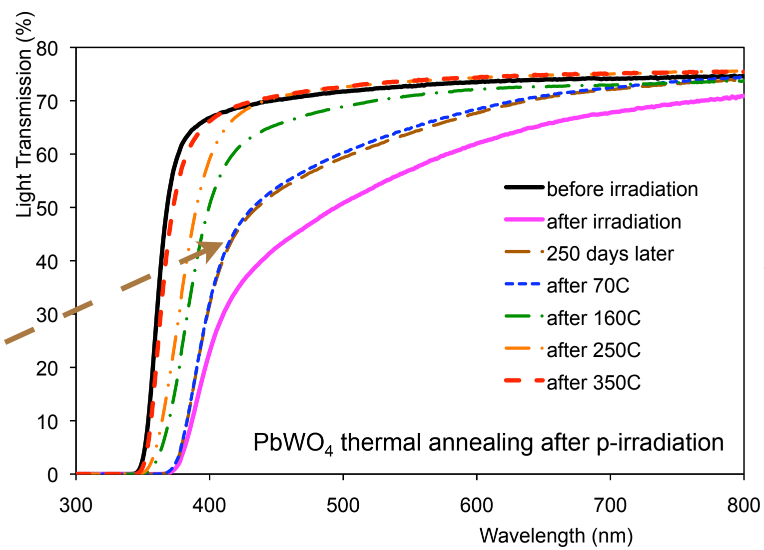

Remark 1:

Hadron-specific damage (band-edge shift) recovers by thermal annealing up to 350°C (crystal d)

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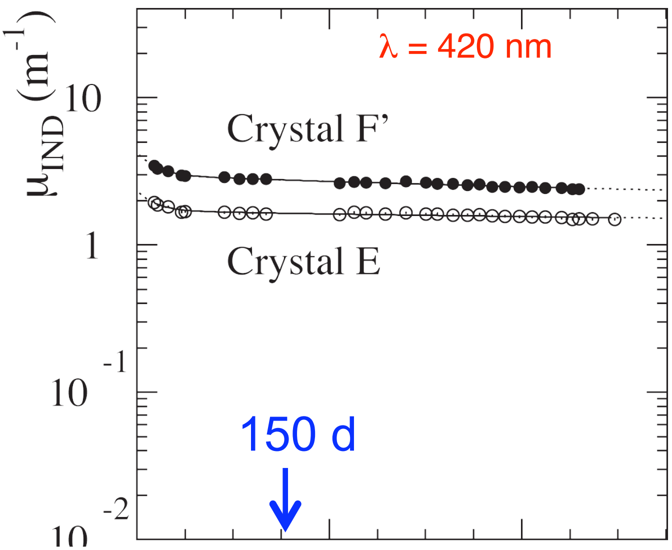

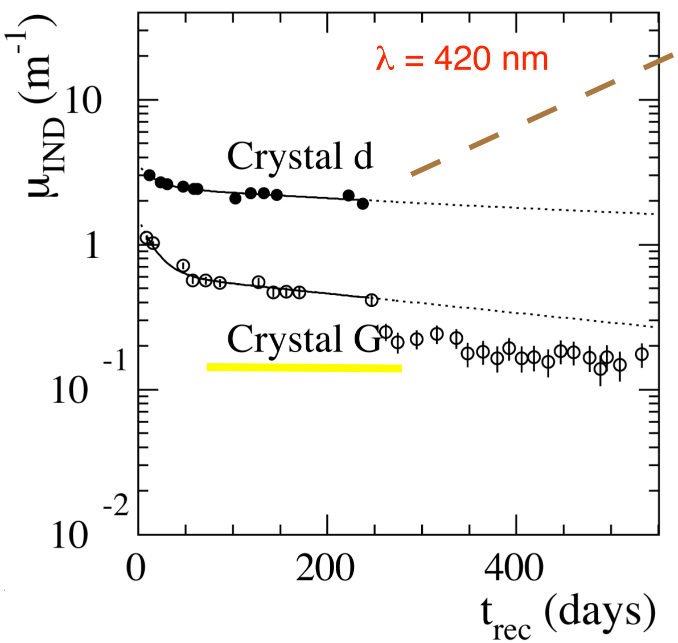

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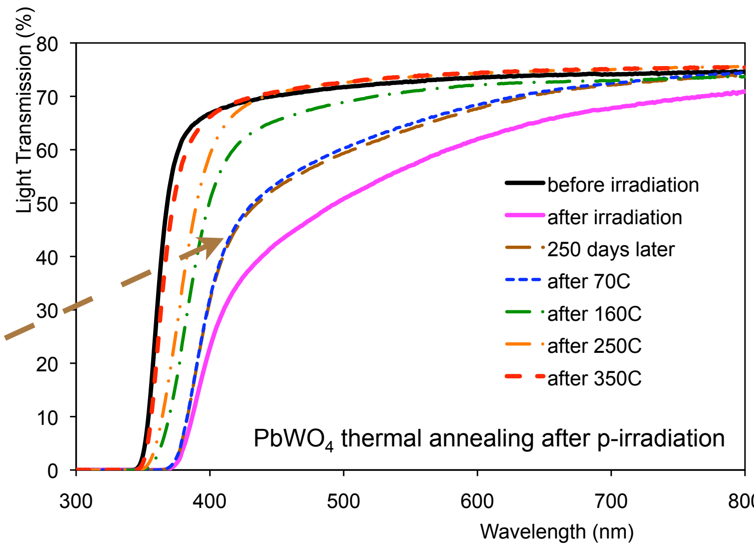

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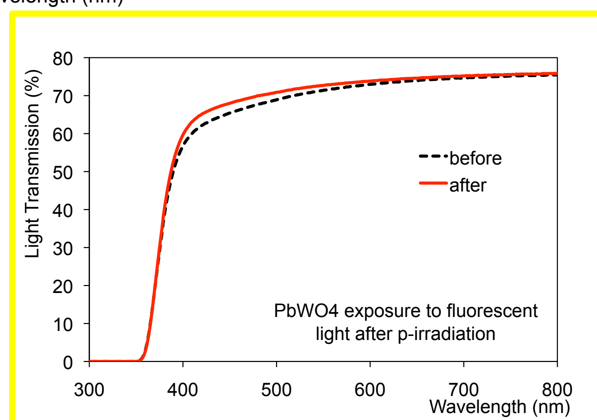
Hadron-specific damage (band-edge shift) recovers by thermal annealing up to 350°C (crystal d)

Remark 2:

An accidental exposure to fluorescent light induced some recovery, but no band-edge recovery (crystal G)



Understanding of hadron damage mechanism in $PbWO_4$

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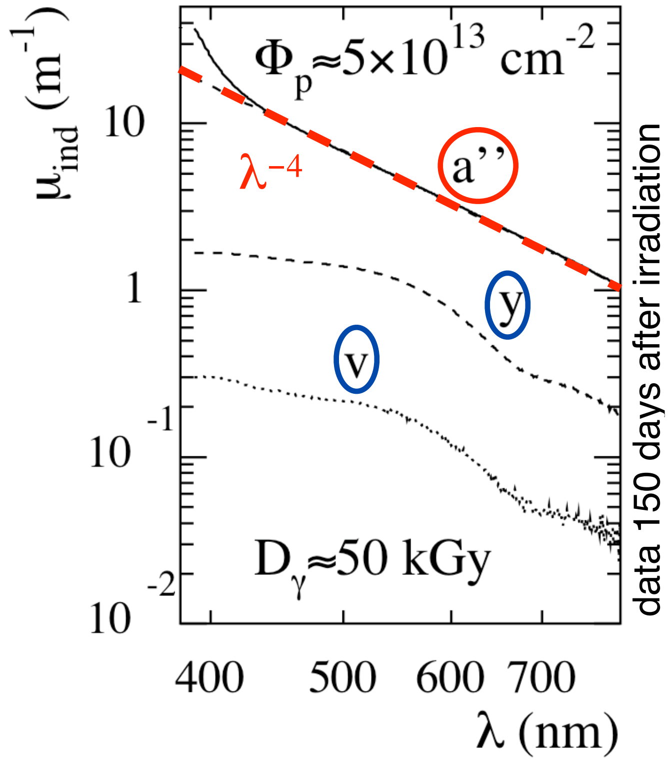
$\mu_{IND}(\lambda)$ is qualitatively different between proton- and γ-irradiated crystals:

In proton-damaged crystals, dominant component has a Rayleigh-scattering behavior = scattering off "dipoles" with dimension < λ :

- → λ^{-4} dependence (see crystal *a"*)
- → scattered light completely polarized



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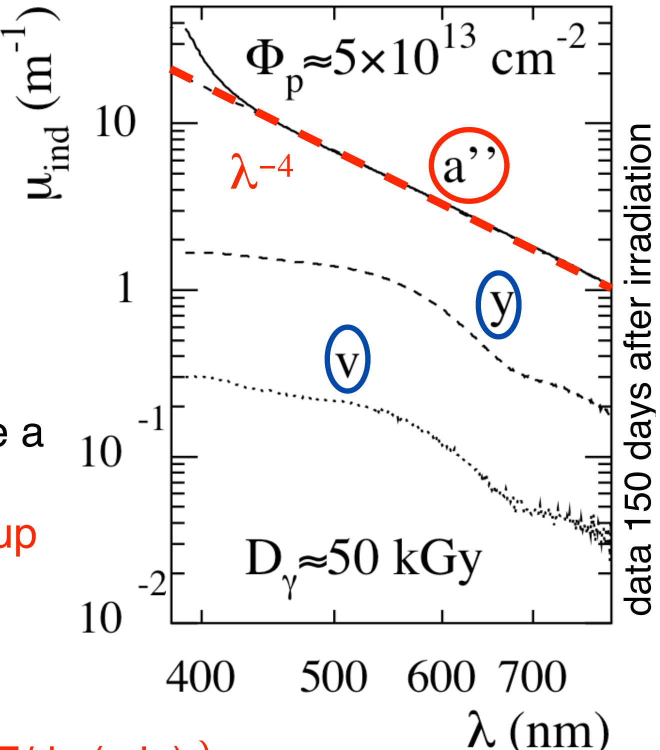

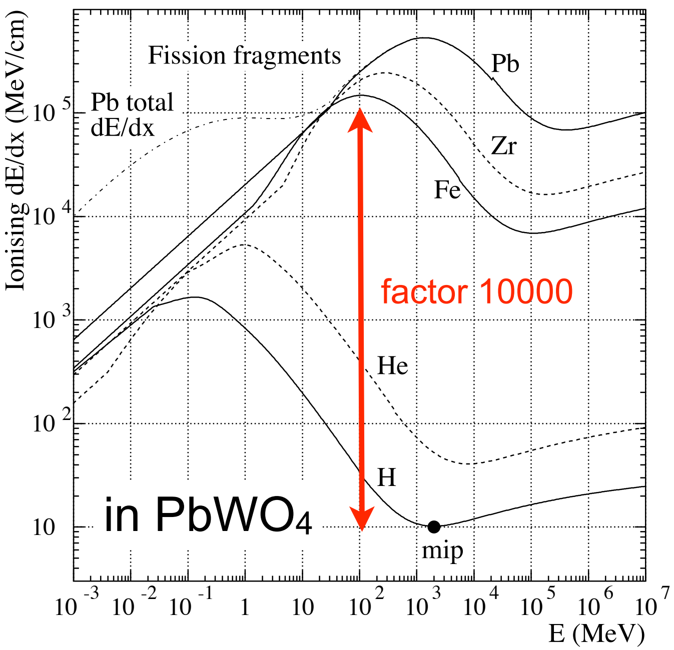

Consistent with:

Fission of Pb and W above a ~20 MeV threshold, with production of heavy breakup fragments

- → range ≤ 10 μm
- → E ≤ 100 MeV
- → dE/dx ≃ $\mathcal{O}$(10000 x dE/dx (mip))

Along their track, the crystal structure is changed permanently
➛ dipole-like inclusions

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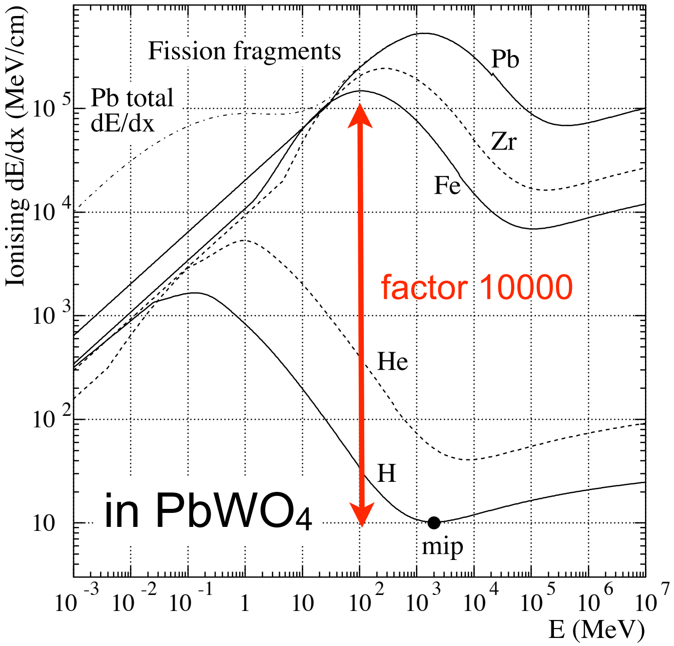

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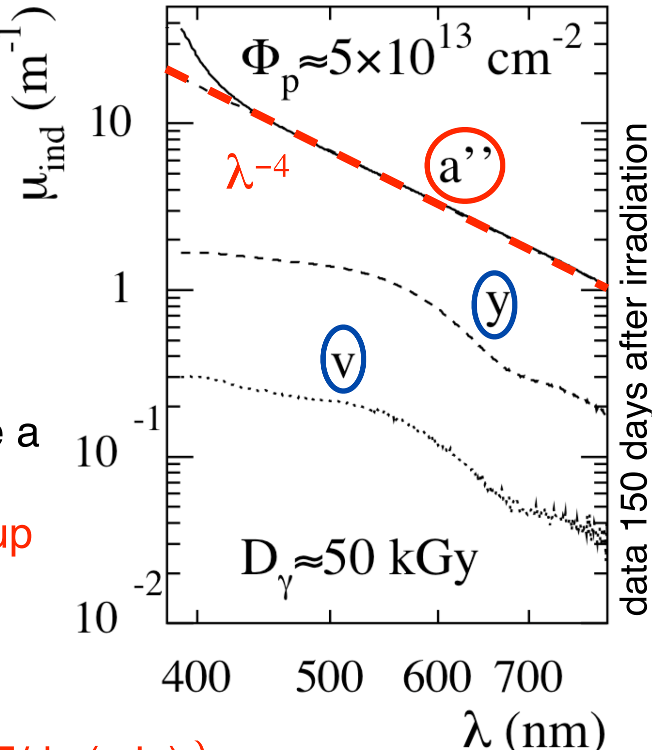

Along their track, the crystal structure is changed permanently
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→ This feature of damage should be absent for crystals with elements with Z<71
A hadron damage test in crystals containing only such elements should confirm the present understanding of damage mechanisms ➛ Test CeF_3 and LYSO

Proton-irradiation test of Cerium Fluoride

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Apply same irradiation and measurements procedures used for $PbWO_4$

→ CeF_3:Ba crystal from Optovac from the '90s, 21 x 16 x 141 mm³ (8.4 X_0)

→First 24 GeV/c p-irradiation up to $\Phi_p = (2.78 \pm 0.2) \times 10^{13}\, p/cm^2$
followed by recovery measurements over more than 1 year

→*F. N. et al., IEEE NSS Dresden 2008*

→Second irradiation up to $\Phi_p = (2.12 \pm 0.15) \times 10^{14}\ \mathrm{p/cm^2}$
followed again by recovery measurements over more than 1 year

→ Transmission damage evaluated at λ where peak of scintillation emission, for Ba-doping ~ 340 nm, according to:

W.W. Moses & S.E.Derenzo, IEEE TNS 36 (1989) 173-176
Crystal Clear Coll., S.Anderson et al., NIM A 332 (1993) 373-394
E. Auffray et al., NIM A 383 (1996) 367-390

CeF_3 Transmission changes with proton irradiation

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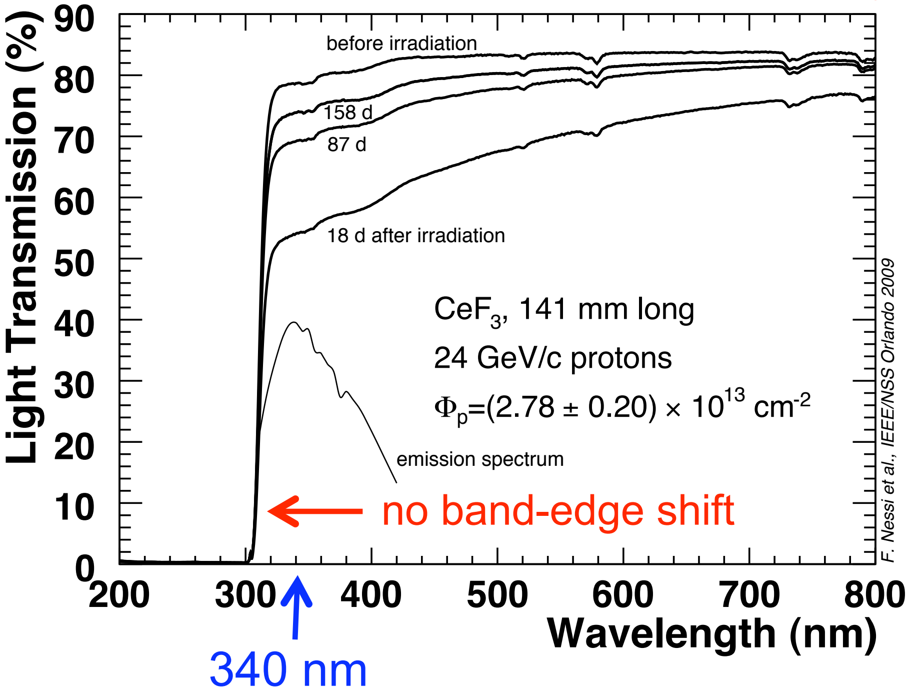
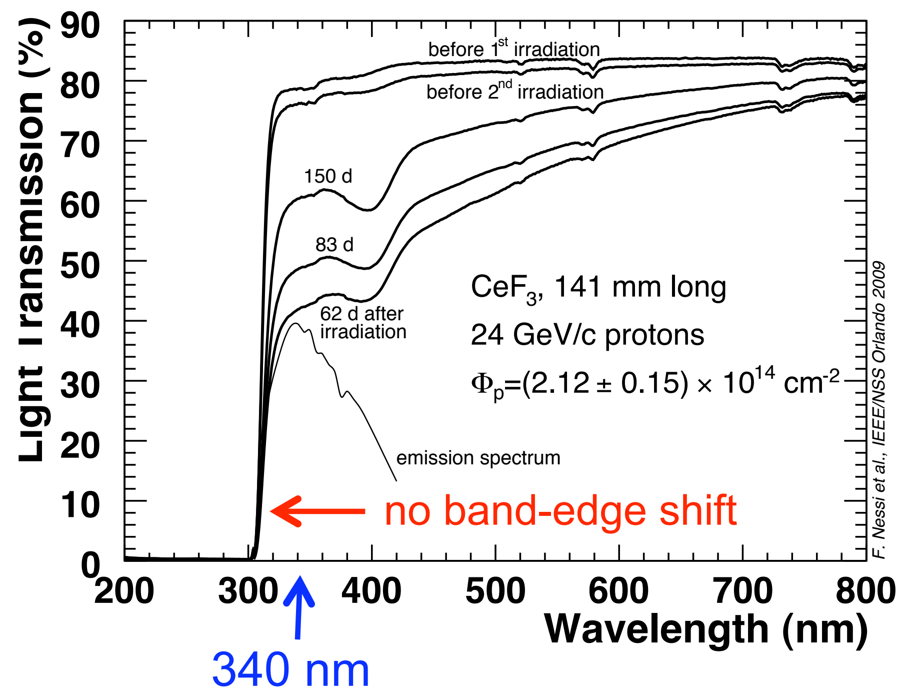
important recovery over a few months





→ light transmission recovers for all λ, except for an absorption band that seems cumulative, sitting however where the emission drops off.

→ evaluate damage further at the peak-of-emission $\lambda = 340$ nm

CeF_3 Light absorption after p irradiation

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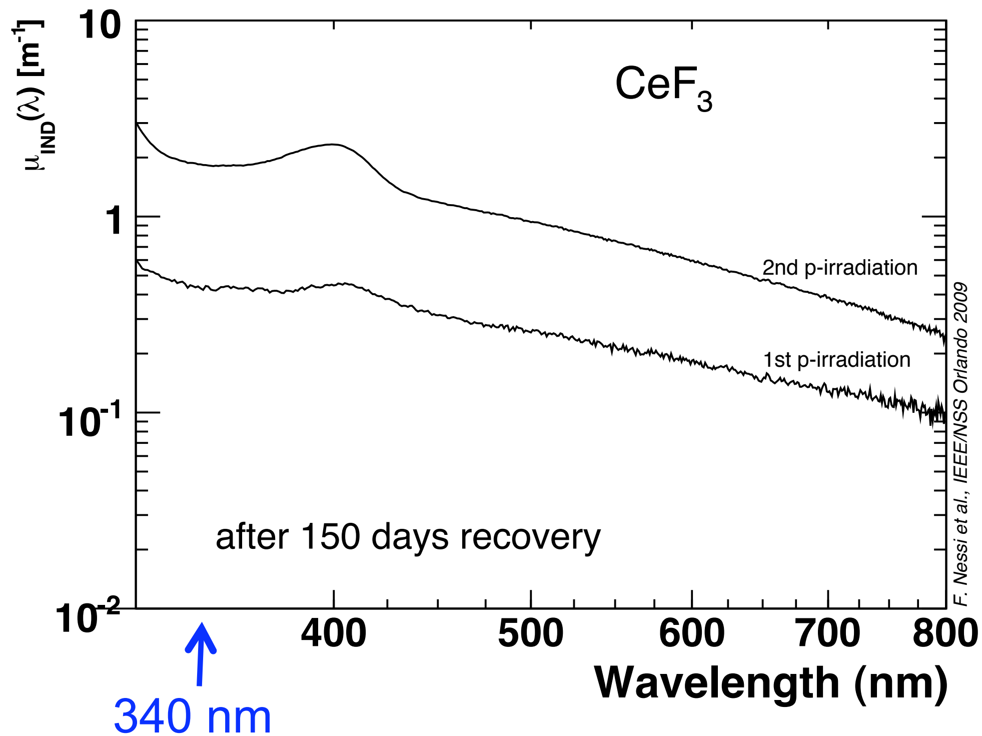
- Rayleigh scattering behavior, as observed for $PbWO_4$ over most of the λ range (see slide 9), is not present

→ this confirms that the dominant Rayleigh scattering ovserved in $PbWO_4$ is linked to the production of highly ionizing heavy fragments



Interest of LYSO

→ Calorimetry at sLHC will have to perform through ~7 x LHC hadron fluence

→ LYSO is not expected to fission, since Lu has Z=71, and could possibly not be subject to damage from highly ionizing fragments

→ LYSO is being mass produced by several companies, in particular for PET applications. The capability to grow large ingots has been demonstrated already.

→ LYSO has a very high light yield, and could thus perform adequately even with radiation losses

→ γ-radiation effects have been shown to be small, and not dose rate dependent

R.H.Mao, L.Y.Zang and R.Y. Zhu, IEEE TNS 54 (2007) 1319

→ LYSO could be a candidate for sLHC calorimetry

→ The p-irradiation of LYSO will deepen our understanding of hadron damage in crystals

Proton-irradiation test of LYSO

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Apply same irradiation and measurements procedures used for $PbWO_4$ and CeF_3

→ LYSO:Ce crystal from SIC, 25 x 25 x 100 mm^3 (8.8 X_0)

→First 24 GeV/c p- irradiation up to a fluence

$$\Phi_p = (0.89 \pm 0.06) \times 10^{13}\ \mathrm{p/cm^2}$$

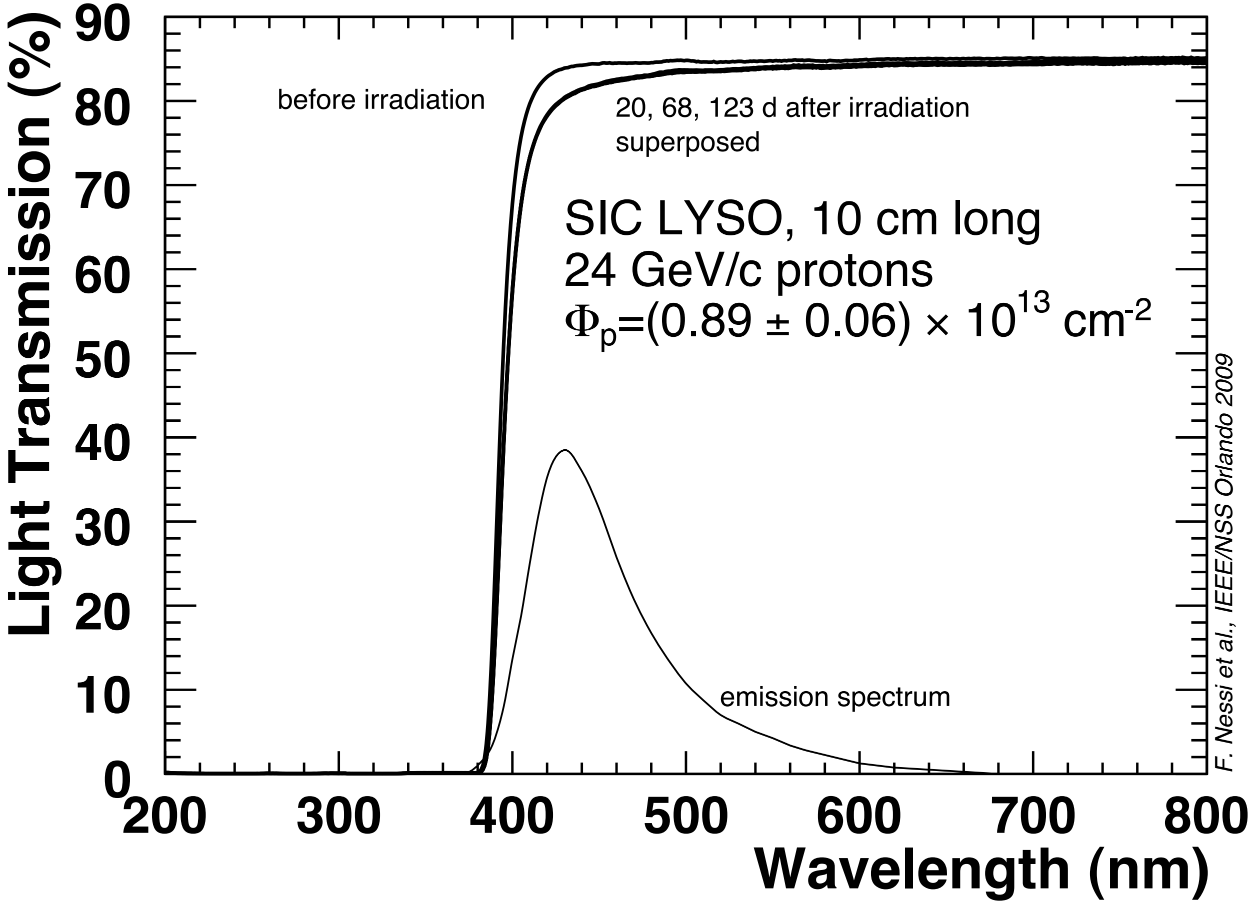
at a flux $\phi_p = (0.60 \pm 0.04) \times 10^{13}\ \mathrm{p/cm^2/h}$

followed by recovery measurements over 5 months

→ Transmission damage evaluated at λ where peak of scintillation emission, from radioluminescence ~ 430 nm, according to:

R.H.Mao, L.Y.Zang and R.Y. Zhu, IEEE TNS 55 (2008) 1759

LYSO Transmission changes with proton irradiation



→ The change in Transmission induced by p-irradiation at this fluence in LYSO is quite modest

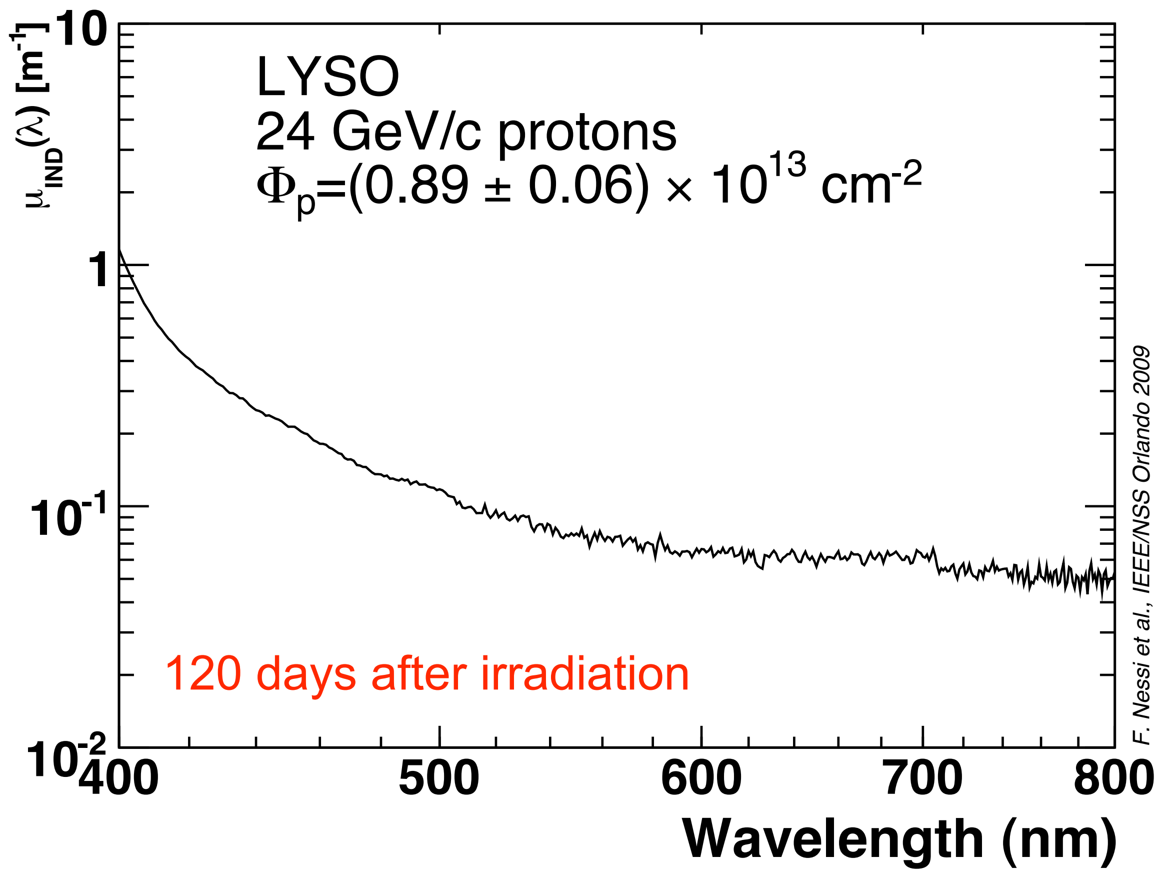
→ No recovery overall is observed between 20 days and 123 days after irradiation

LYSO Light absorption after p irradiation

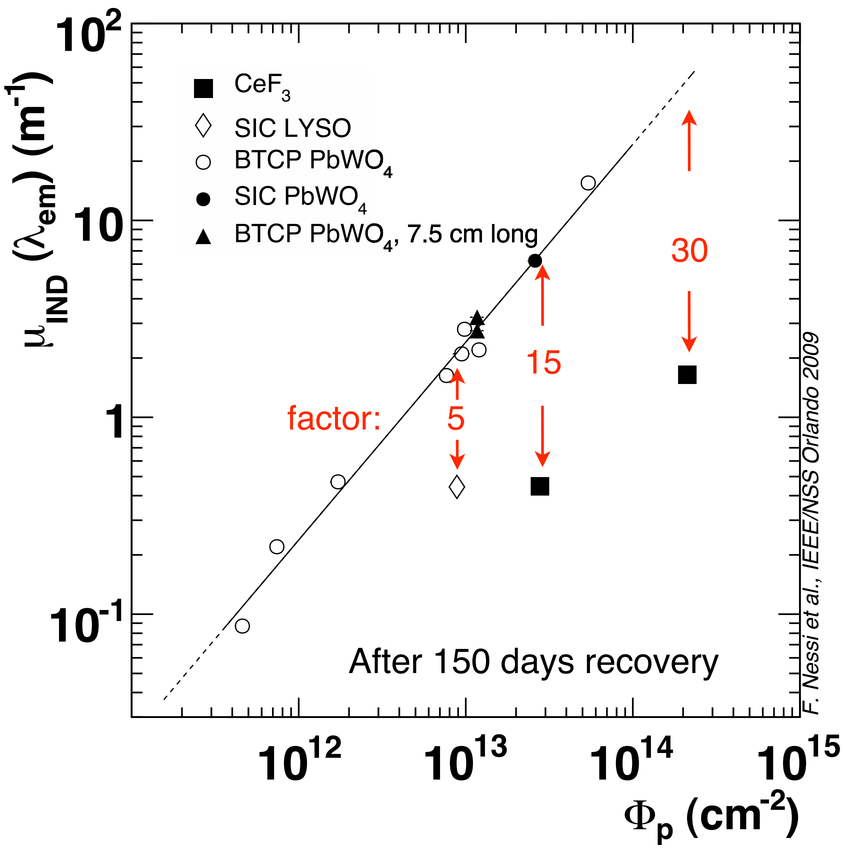
→ In LYSO, as in CeF_3, Rayleigh scattering behavior, as observed for $PbWO_4$ over most of the λ range (slide 9), is not present

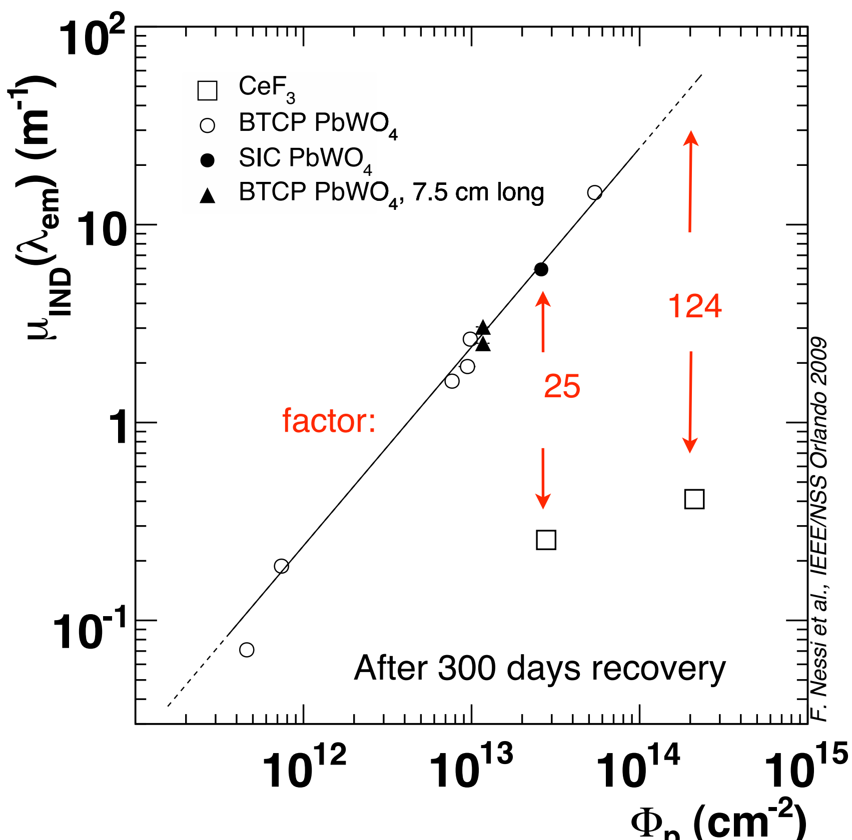
→ this is a further confirmation of our qualitative understanding, that the dominant Rayleigh scattering we observe in $PbWO_4$ is linked to the production of highly ionizing heavy fragments.

Such fragments -as anticipated- do not seem to be present in LYSO



Damage amplitudes versus p-fluence





→ In $PbWO_4$ a fraction of the damage has a component with $\tau \gg 1$ years : "permanent". Values at 150 d do not change further. Damage is cumulative

→ In CeF_3 damage recovers, thus choice of time after irradiation for comparisons arbitrary. Damage is not cumulative.

→ In LYSO we observe no damage recovery so far. A second irradiation, at ~10 x fluence, will tell us whether there is any cumulative damage

Conclusions

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- A hadron-specific, cumulative damage from charged hadrons has been observed in $PbWO_4$, which only affects light transmission. All characteristics of the damage are consistent with it being mainly due to an intense local energy deposition from heavy fission fragments.

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- Measurements of proton-induced absorption up to $\phi_p = 2x10^{14}$ p/cm^2 in CeF_3 show a damage which recovers at room-T and is not cumulative

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- Hadron damage is not entirely about color centers. It is also about nuclear interactions and displacement of atoms!