Studies of Hadron Damage in Lead Tungstate and Cerium Fluoride Crystals

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CMS upgrade workshop, Fermilab, November 2008

High hadron fluxes

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Questions

Is there a specific, possibly cumulative damage from hadrons?

If so, what is its quantitative importance?

Does it affect the light transmission only, and can thus be “easily” monitored?

Does it alter the scintillation mechanism?

→ Systematic study on $PbWO_4$ *(*)*

Can we confirm our qualitative understanding of hadron effects in $PbWO_4$ through complementary measurements?

How do different crystal types perform in high hadron fluences?

→ Study CeF_3 *(**)*

(*) On BTCP crystals of production quality.
(**) This was the CMS ECAL crystal type in the CMS LOI, CERN/LHCC 92-3, LHCC/1, October 1992

Transmission changes in $PbWO_4$ for 20 GeV/c protons and ^{60}Co γ

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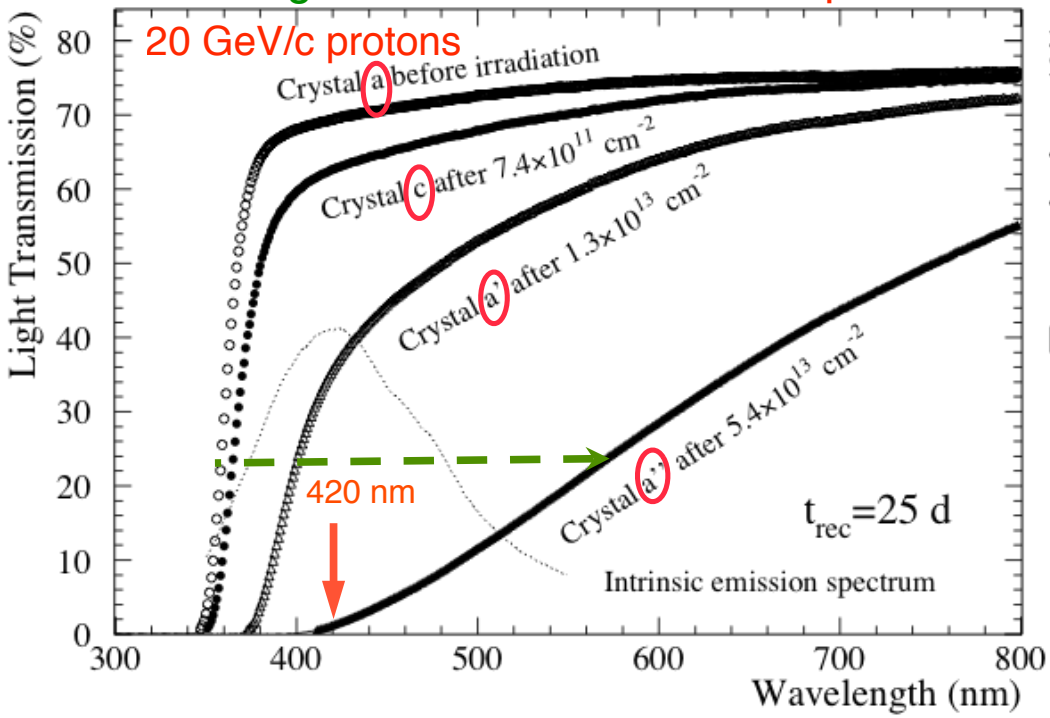
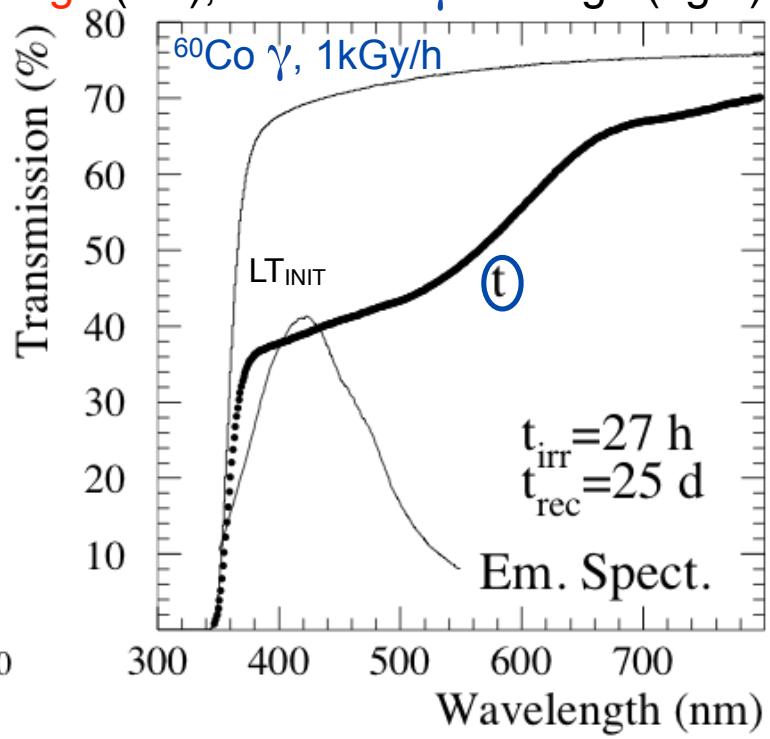
M. Huhtinen, P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, Nucl. Instr. Meth. A545 (2005) 63-87

→ A band-edge shift(*) is observed with proton-damage (left), unlike for γ-damage (right)





' (") indicates a second (third) irradiation of the same crystal

(*) probably due to disorder causing an Urbach-tail

→ Quantify damage through the induced absorption coefficient μ_{IND} in Longitudinal Transmission (LT) of 23 cm long crystals:

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

Features of $PbWO_4$ Transmission after p and γ irradiation

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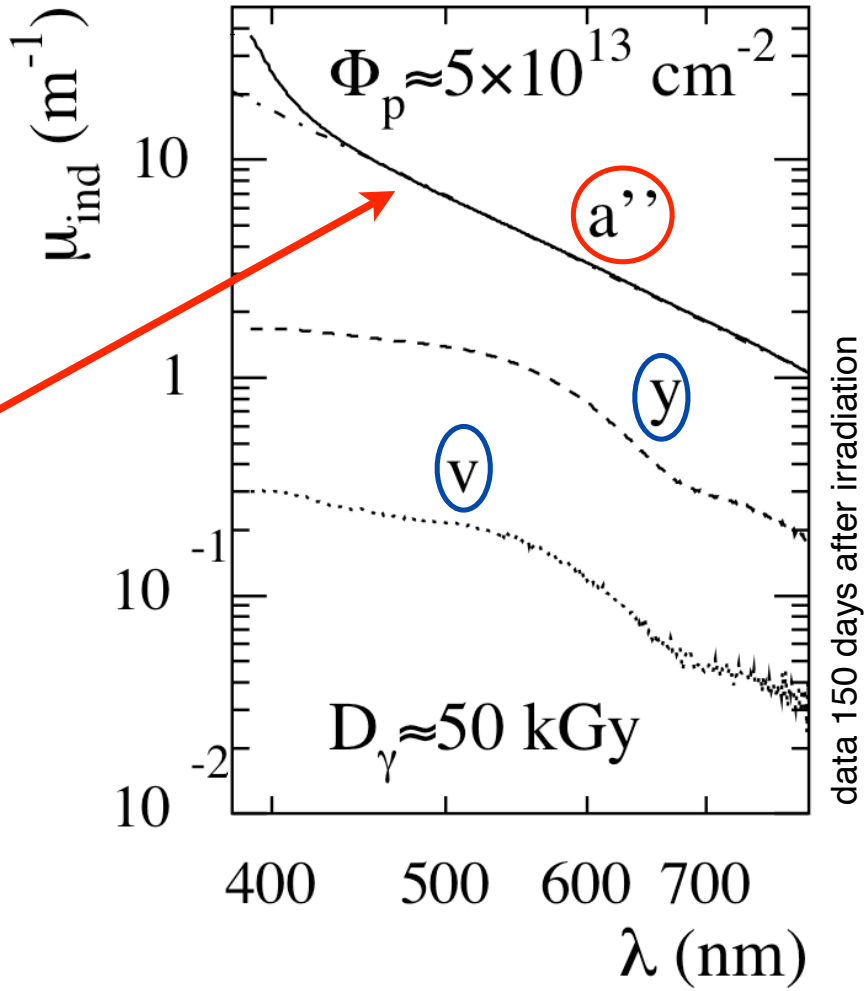
→ $\mu_{IND}(\lambda)$ is qualitatively different between proton - and γ-irradiated crystals

→ In proton-damaged crystals, a dominant component with a Rayleigh-scattering behavior is observed: the scattered light is completely polarized, and a fit to the data (see crystal *a"*) shows

$$\mu_{IND}(\lambda) \propto \frac{1}{\lambda^4}$$

→ This behavior is not observed for γ-damaged crystals (v, y)



Transmission recovery in $PbWO_4$ after p-irradiation

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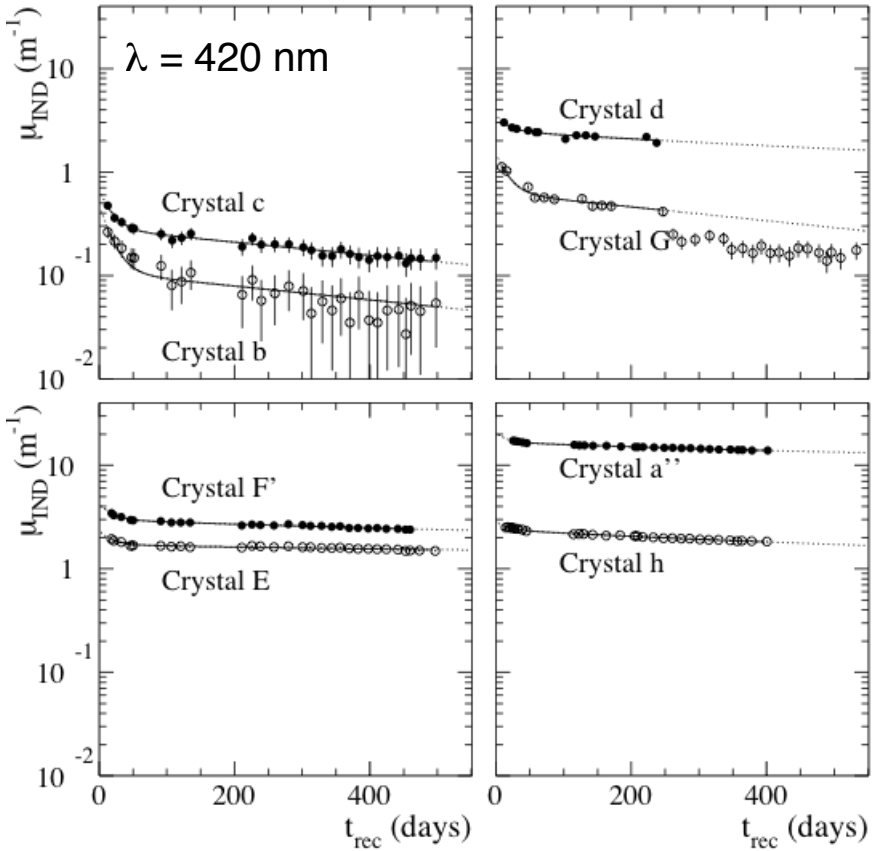
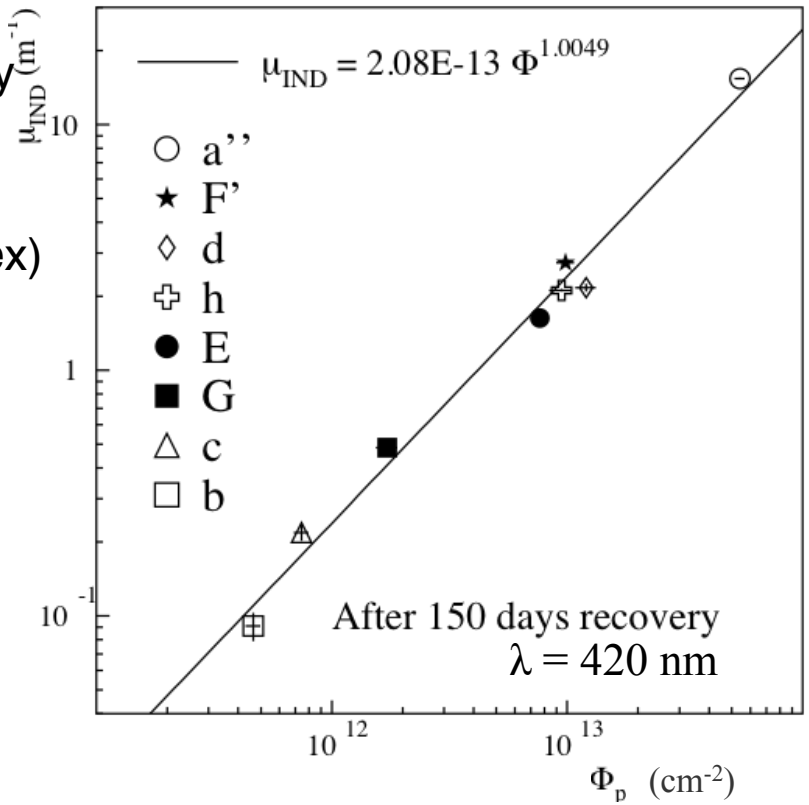
Damage recovery over time on a set of crystals irradiated up to different fluences can be globally fitted by

$$\mu_{IND}(420\ nm, t_{REC}) = \sum_{i=1}^{2} A_i^j e^{-t_{rec}/\tau_i} + A_3^j$$

(τ_1 = 17.2 days and τ_2 = 650 days, j=crystal index)





→Proton-induced damage increases linearly with fluence: it is cumulative

→No flux dependence observed: flux was varied from $5x10^{11}$ (crystal h) to 10^{12} (a'',b,c,d) to 10^{13} p/cm²/h (E,F',G)

Correlation between changes in LT and in Light Output in $PbWO_4$

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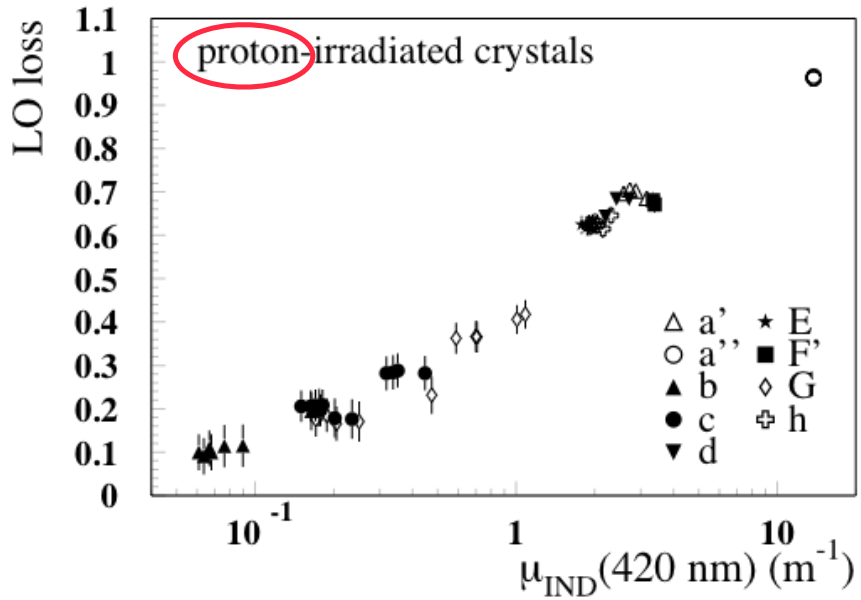
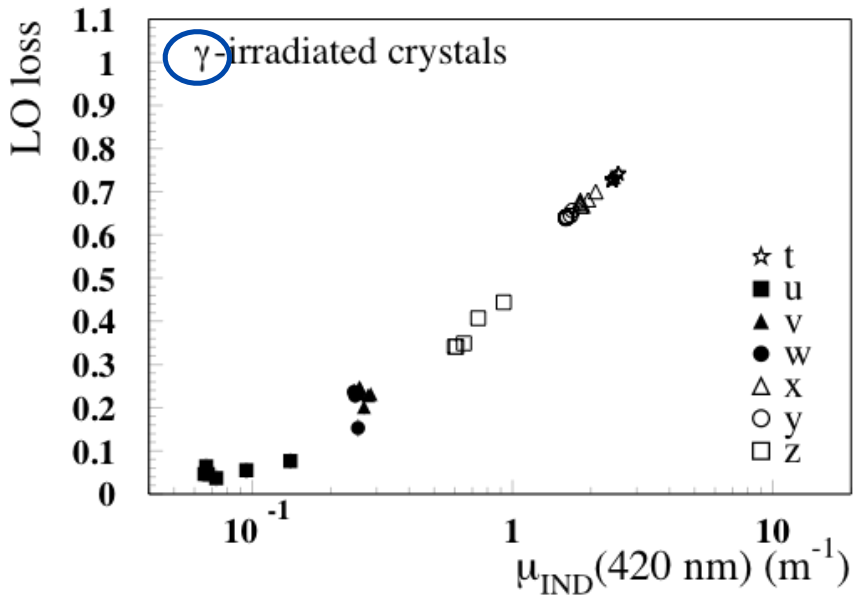
P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, Nucl. Instr. Meth. A564 (2006) 164-168

Correlation between changes in LT and in Light Output for $PbWO_4$





→ Correlation between μ_{IND} (420 nm) and Light Output loss for crystals irradiated with protons

→ Correlation between μ_{IND} (420 nm) and Light Output loss for crystals irradiated with γ from a ^{60}Co source

Within the precision of the measurement, the two correlations are compatible

→ No additional, hadron-specific damage to the scintillation mechanisms observed

Comparison between proton and pion damage in $PbWO_4$

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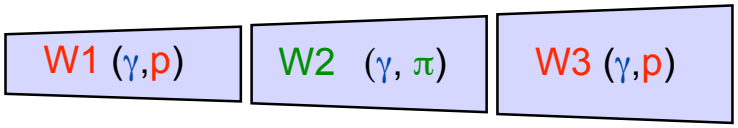
P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, D.Renker, Nucl. Instr. Meth. A587 (2008) 266-271

Hadron fluxes in LHC typically due to charged pions with a few hundred MeV energy

A test with lower-energy pions was needed to establish how to scale between ~20 GeV/c protons and a lower-energy hadrons like expected during LHC running



Crystal W was cut into 3 sections, W1, W2 and W3, each 7.5 cm (8.4 X_0) long

- W1 and W3 were irradiated with 24 GeV/c protons up to

$$\Phi_p = (1.17 \pm 0.11) \times 10^{13}\ \mathrm{p/cm^2}$$

- W2 was irradiated with a 290 MeV/c π^+ flux of $\varphi_\pi = 4.13 \times 10^{11}\ \pi\ /\mathrm{cm^2/h}$ up to a fluence of

$$\Phi_\pi = (5.67 \pm 0.46) \times 10^{13}\ \pi/\mathrm{cm^2}$$

→ LT shape similar after p and π irradiations

→ Band-edge shift present for π as well

→ p and π damage recovery show compatible time constants

Damage profile in $PbWO_4$: Transverse Transmission

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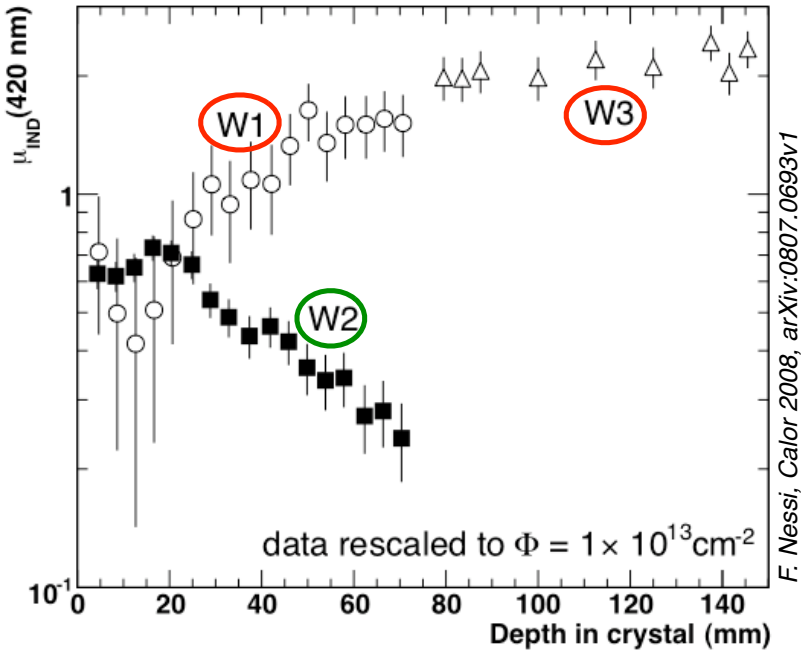
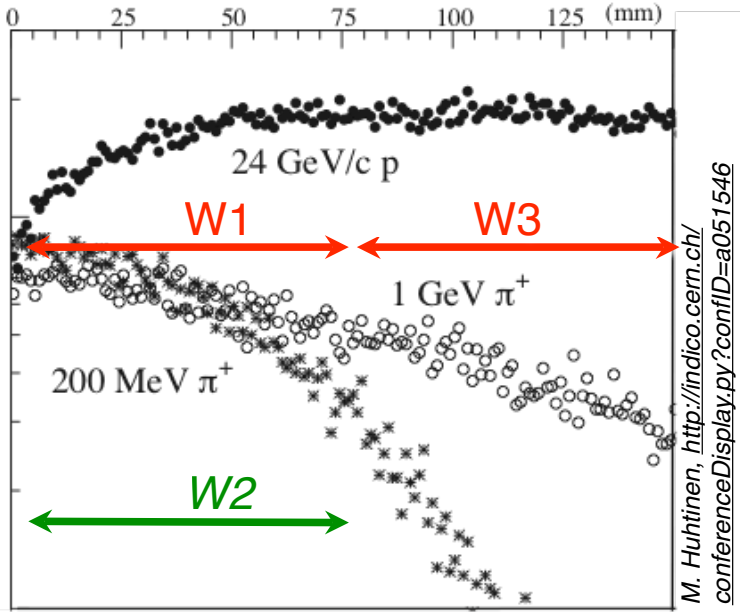
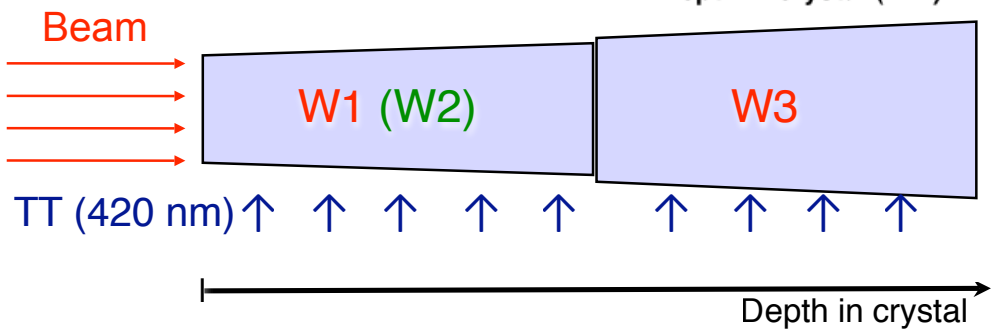
measured induced absorption coefficients



Star density profiles from FLUKA simulation





→ The damage profile is the same as the density profile of stars*

→ To predict expected hadron damage in a different environment, rescale a measured μ_{IND} by the star density ratio and luminosity ratio from MC calculations

**inelastic hadronic interaction caused by a projectile above a given energy threshold*

Understanding of hadron damage mechanism in $PbWO_4$

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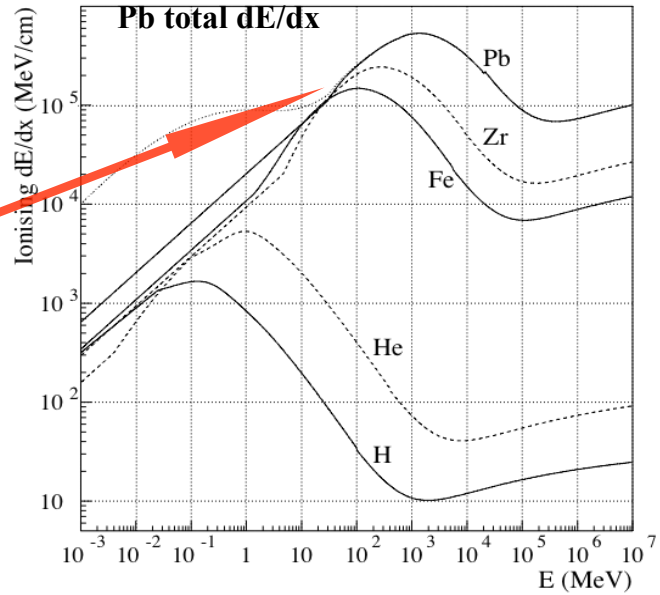
Summary of hadron damage in $PbWO_4$:

→Tested over 2 orders of magnitude in fluence, up to $5x10^{13}$ /cm^2 , i.e. $\eta \approx 2.0$ at sLHC.
→For fluxes between $4x10^{11}$ /cm^2/h and 10^{13} /cm^2/h no rate dependence observed
→ Its non-recovering component grows linearly with fluence
→ It only affects Light Transmission, and can thus be monitored
→ We detect no alteration in the scintillation mechanism
→ Scaling between proton and π^+ consistent with star density ratios from FLUKA
→ It has a Rayleigh-scattering behavior = scattering off "dipoles" with dimension < λ

Observations consistent with the peculiarities of hadron damage in $PbWO_4$:

Above ~20 MeV threshold, production of heavy fission fragments, with up to 10 µm range, typical E up to 100 MeV and energy loss along their path up to 50000 x mip

Along their track, the crystal structure is changed permanently



Proton-irradiation test of Cerium Fluoride

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G.Dissertori, D.Luckey, P.Lecomte, F.Nessi-Tedaldi, F.Pauss, D.Renker, IEEE/NSS Dresden, October 2008

After the pioneering work of understanding CeF_3 luminescence...

F.A. Kröger & J. Bakker, Physica VIII (1941) 628-646

and the discovery of its properties as a scintillator...

D.F. Anderson, IEEE TNS 36 (1989) 137-140
W.W. Moses & S.E. Derenzo, IEEE TNS 36 (1989) 173-176

it was subject to an intense research program and studies, mainly in the '90:

Scintillation characteristics, production of long crystals, behavior in γ and MeV-neutron irradiations, matrix performance in particle beams. E.g.:

M. Kobayashi et al., NIM A 302 (1991) 443-446
Crystal Clear Coll., S.Anderson et al., NIM A 332 (1993) 373-394
R. Chipaux et al., NIM A 345 (1994) 440-444
E. Auffray, F.N.-T., P. L. et al., NIM A 378 (1996) 171-178
R. Novotny et al., NIM A 486 (2002) 131-135

Present rekindled interest:

- Calorimetry at sLHC will have to perform through ~7 x LHC hadron fluence.
- CeF_3 in not expected to exhibit fission, since its elements lie below the fission barrier of Z=71 (*A.S.Iljinov et al.,Phys. Rev. C 39 (1989) 1420-1424)*
- The p-irradiation of CeF_3 will deepen our understanding of hadron damage in crystals

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 mm^3 (8.4 X_0)

→ 24 GeV/c p-irradiation at the CERN-PS IRRAD1 facility, up to

$$\Phi_p = (2.78 \pm 0.2) \times 10^{13}\, p/cm^2$$

→First damage measurements 18 days after irradiation (as soon as radioactivity levels sufficiently low for handling)

→Recovery measurements over more than 1 year

→ Evaluate transmission damage at λ relevant for scintillation light collection

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

Emission depends on doping. Roughly centered around ~ 340 nm : use this wavelength for damage evaluation

CeF_3 Transmission changes with proton irradiation

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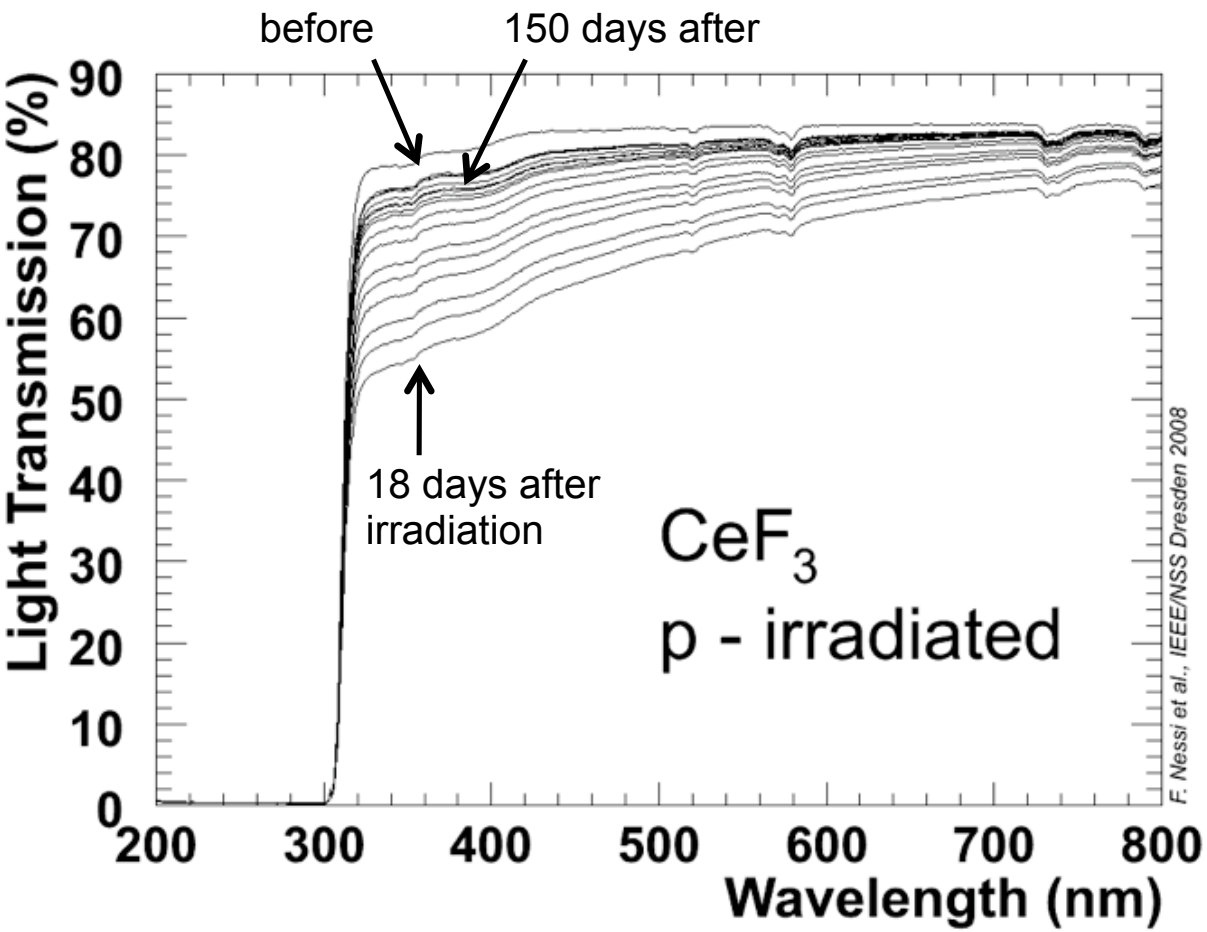

CeF_3 Transmission changes with proton irradiation

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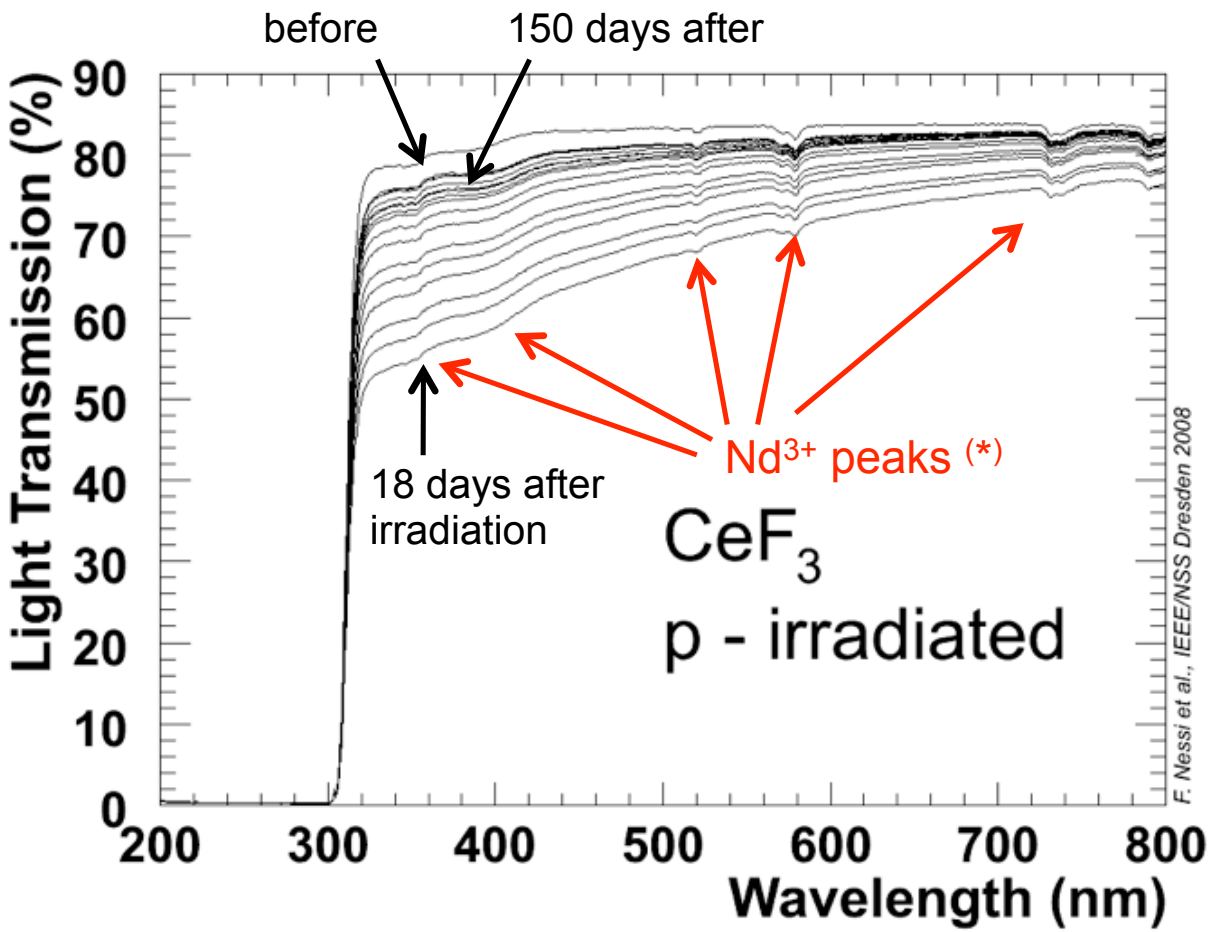

(*) *See e.g. Crystal Clear Collab., E.Auffray et al., NIM A 383 (1996) 367-390*

CeF_3 Transmission changes with proton irradiation

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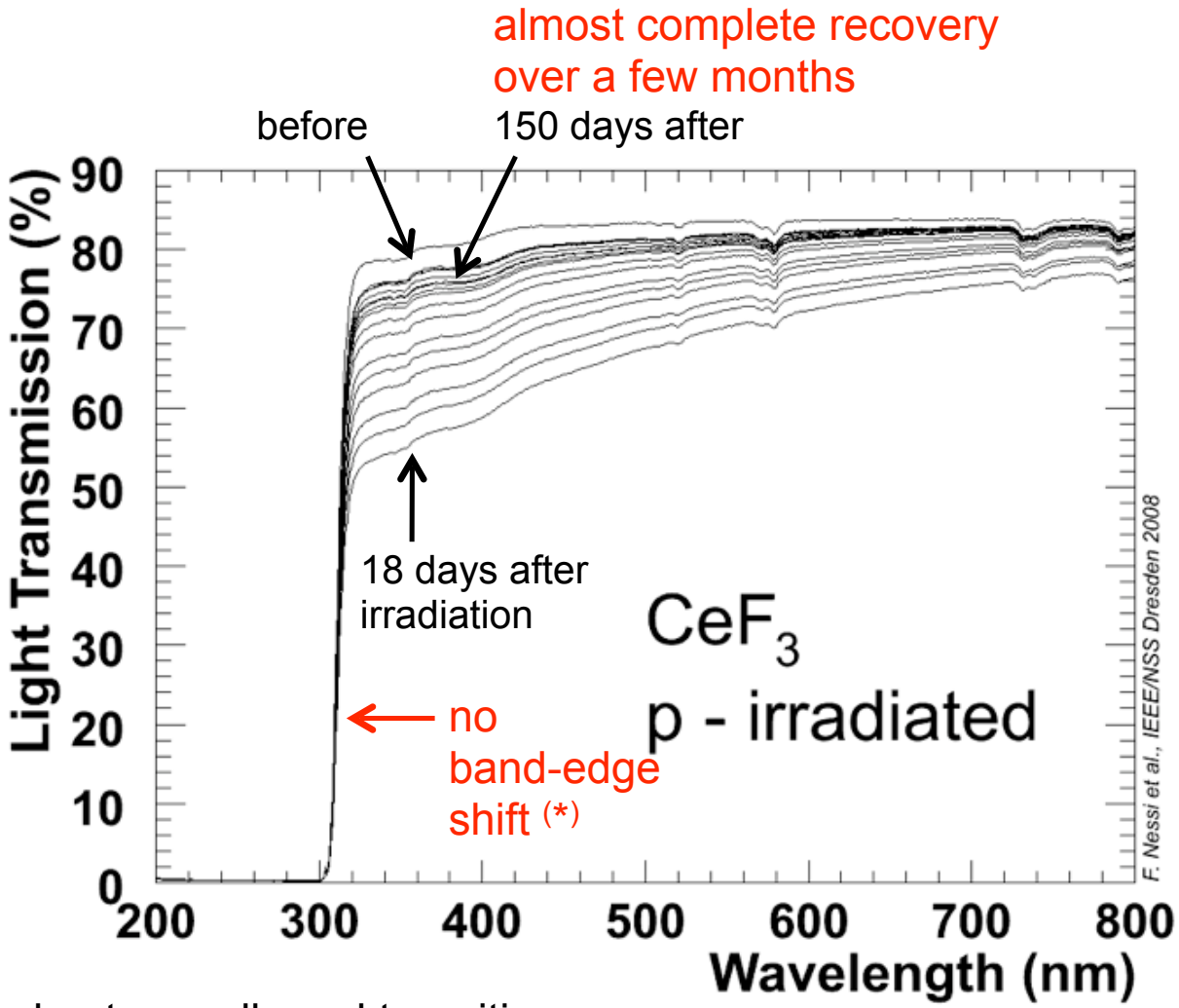

(*) drop is due to an allowed transition *(M.Schneegans NIM A344 (1994) 47-56)* thus remains very steep

CeF_3 Transmission changes with proton irradiation

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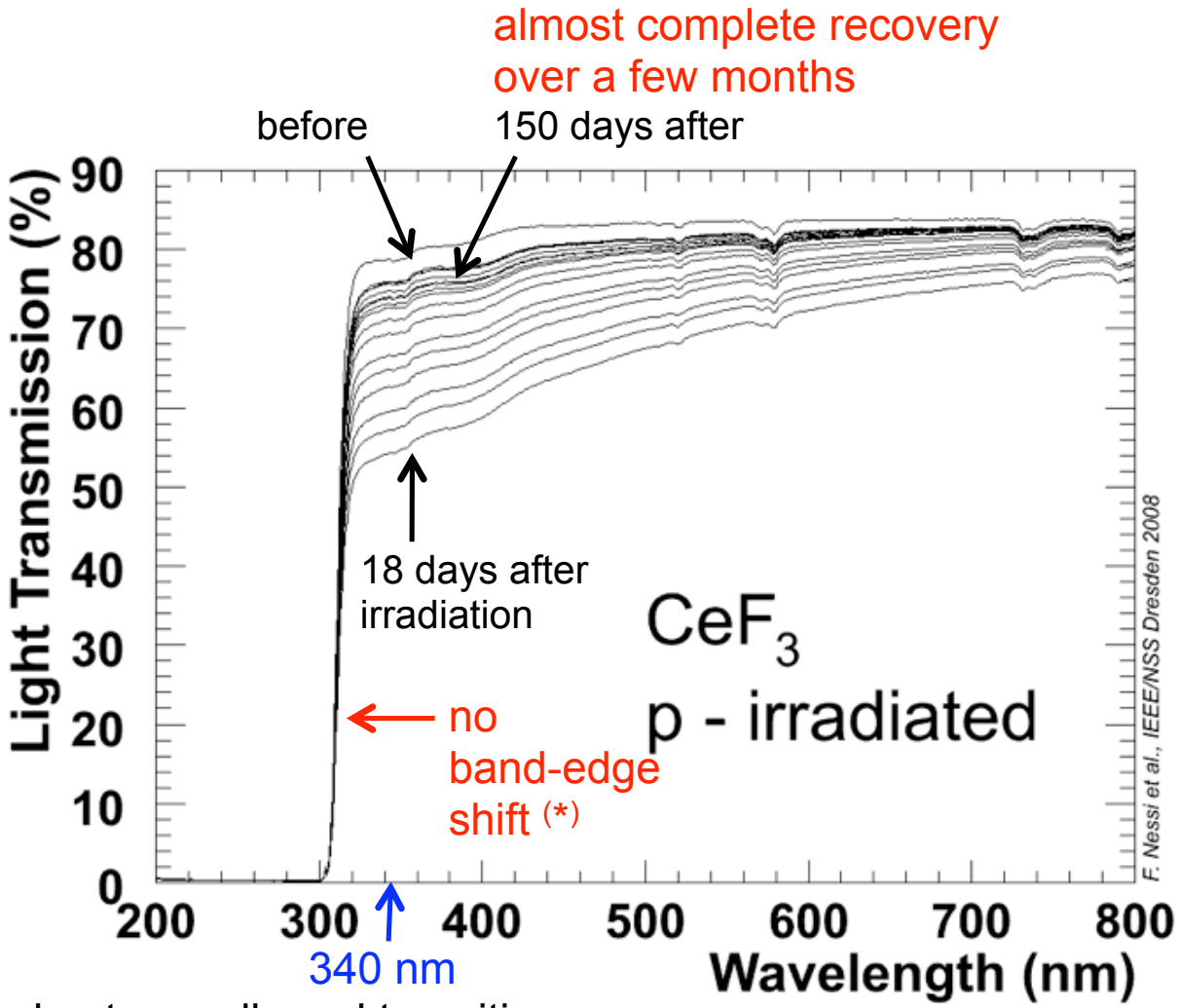

(*) drop is due to an allowed transition *(M.Schneegans NIM A344 (1994) 47-56)* thus remains very sharp

Features of CeF_3 Transmission after p irradiation

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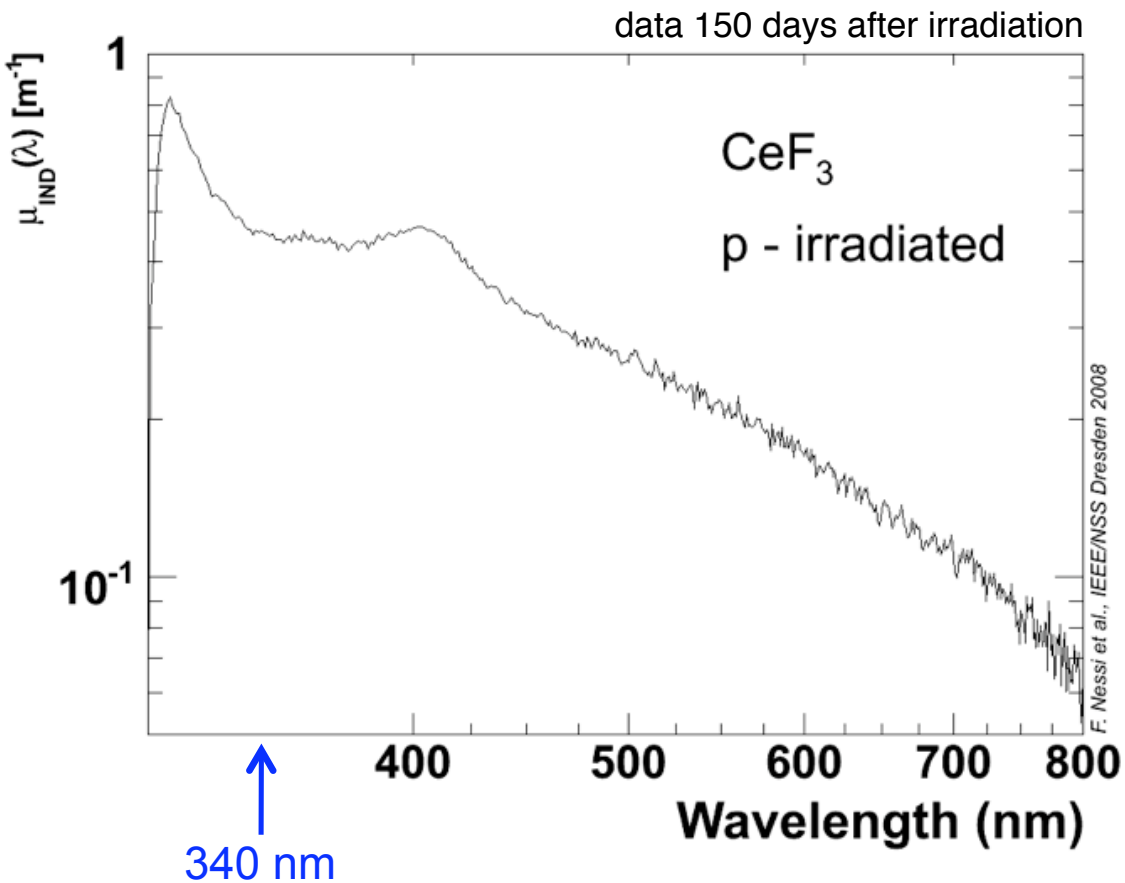
- Rayleigh scattering behavior, as observed for $PbWO_4$ over most of the λ range (see slide 4), is not visible

- This qualitatively confirms our understanding, that the dominant Rayleigh scattering we observe in $PbWO_4$ is linked to the production of highly ionizing fission fragments



Recovery of CeF_3 proton-damage at λ=340 nm

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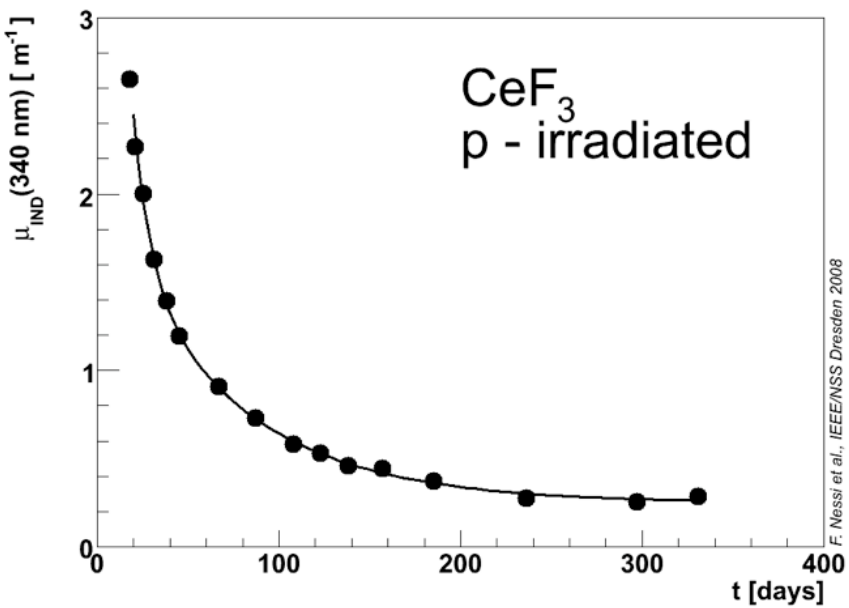
NB: Our measurements are not sensitive to damage components with $\tau \leq$ few days

→90% of the damage observed 18 days after irradiation recovers with $\tau \leq$ 2 months

Notice: such a τ was not observed in γ irradiations (see *Crystal Clear Coll., S.Anderson et al., NIM A 332 (1993) 373-394)*

→The remaining damage has τ >> 1 year

→Whether stable component cumulative, has to be studied.
This is not excluded by MeV-neutron data (*R. Chipaux et al., NIM A 345 (1994) 440-444)*



Proton-damage amplitude in CeF_3 versus $PbWO_4$

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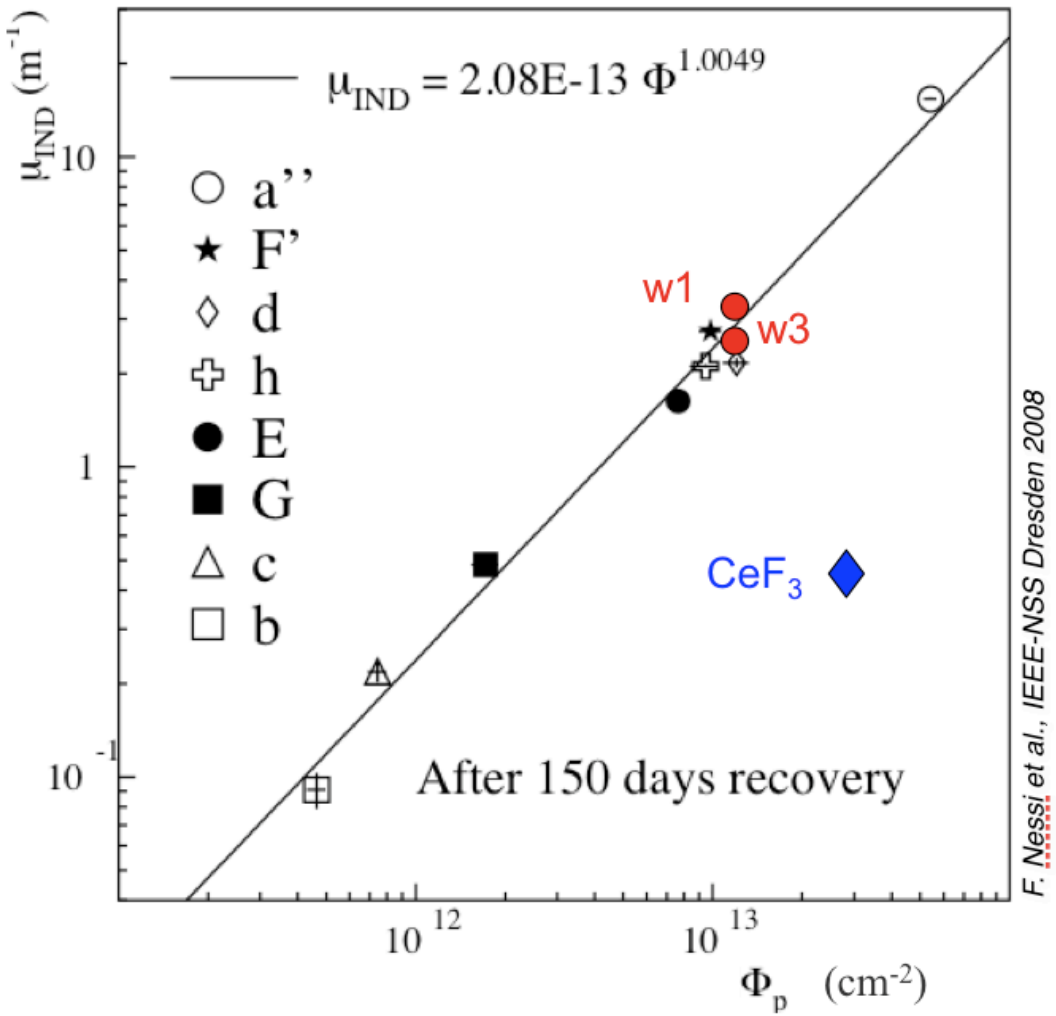
μ_{IND}(420 nm) for 23 cm long $PbWO_4$ shows cumulative damage

μ_{IND}(420 nm) for 7.5 cm long $PbWO_4$ samples w1 and w3 shows same damage, as expected (see slide 10)

μ_{IND}(340 nm) for 14 cm long CeF_3 is a factor 15 smaller at $\phi_p = (2.78 \pm 0.2) \times 10^{13}$ p/cm^2



Conclusions

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

→ Within the explored flux and fluence ranges and the precision of the measurements, this contribution is observed to only affect Light Transmission, and thus can be monitored.

→ Comparative $PbWO_4$ irradiations with protons and pions let us establish that the damage scales with the density of stars from FLUKA simulations. The results can be used to estimate the expected damage for different experimental conditions.

→ Measurements of proton-induced absorption in CeF_3 show a 15 times smaller and qualitatively different damage than in $PbWO_4$.

→The absence of a dominant Rayleigh-scattering component in CeF_3 confirms our understanding, that in $PbWO_4$ it is likely linked to highly-ionizing fission fragments as are produced in crystals with elements above Z=71.

→CeF_3 proton irradiations we will perform at different fluences should allow establishing whether the damage observed is cumulative.

Backup slides

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Light Transmission changes in $PbWO_4$: pions vs. protons

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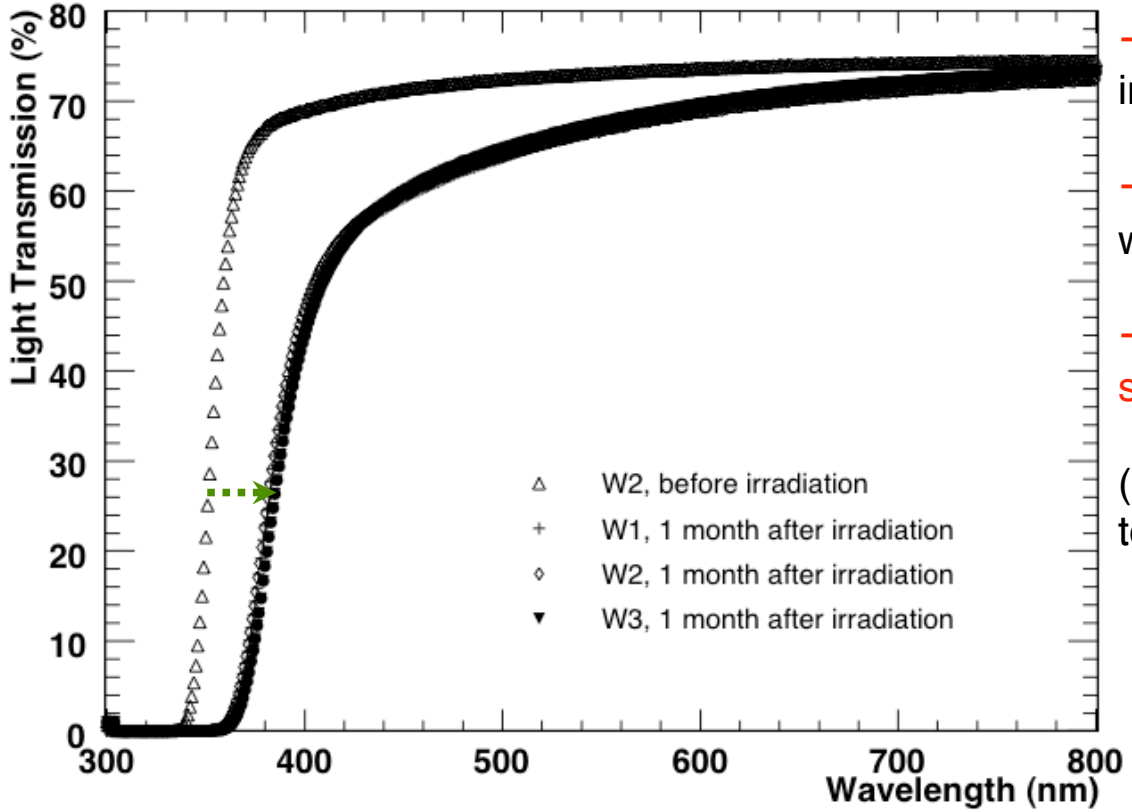
P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, D.Renker, Nucl. Instr. Meth. A587 (2008) 266-271

$\Phi_p = (1.17 \pm 0.11) \times 10^{13}$ p/cm^2 with W1 and W3 placed one in front of the other during irradiation

$\Phi_\pi = (5.67 \pm 0.46) \times 10^{13}$ π/cm^2 for W2



→ LT shape similar after p and π irradiations

→Band-edge shift present for π as well

→ p and π damage qualitatively similar

(magnitude of damage similar, due to suitable choice of fluences)

Transmission recovery in $PbWO_4$ for proton- and π-irradiations

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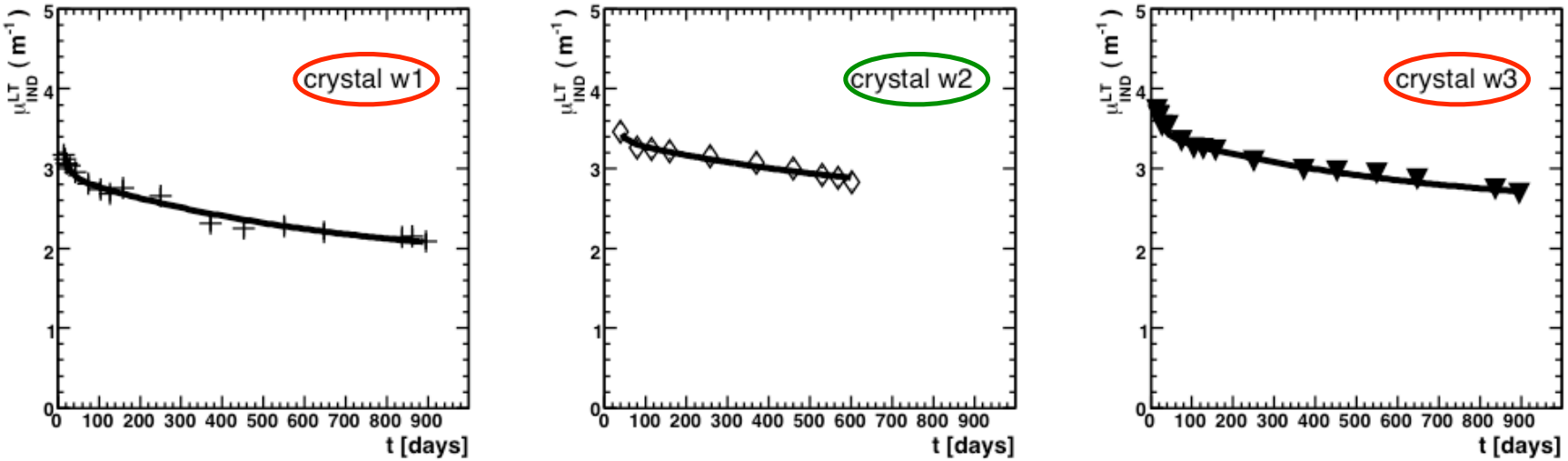
P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, D.Renker, Nucl. Instr. Meth. A587 (2008) 266-271

Damage can be globally fitted as before: $\mu_{IND}(420\ nm, t_{REC}) = \sum_{i=1}^{2} A_i^j e^{-t_{rec}/\tau_i} + A_3^j$

with τ_1 = 17.2 days and τ_2 = 650 days



Low-dose e- and γ irradiations of $PbWO_4$ at IHEP Protvino

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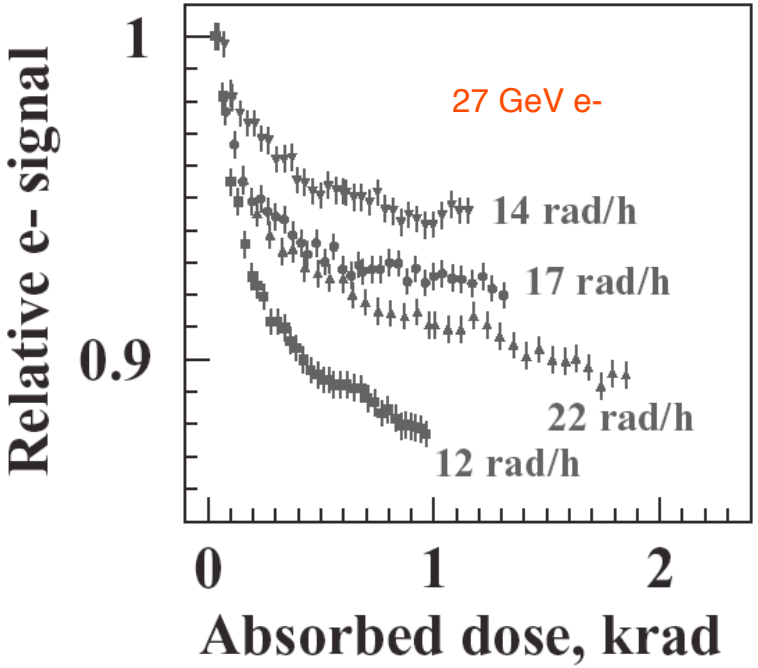
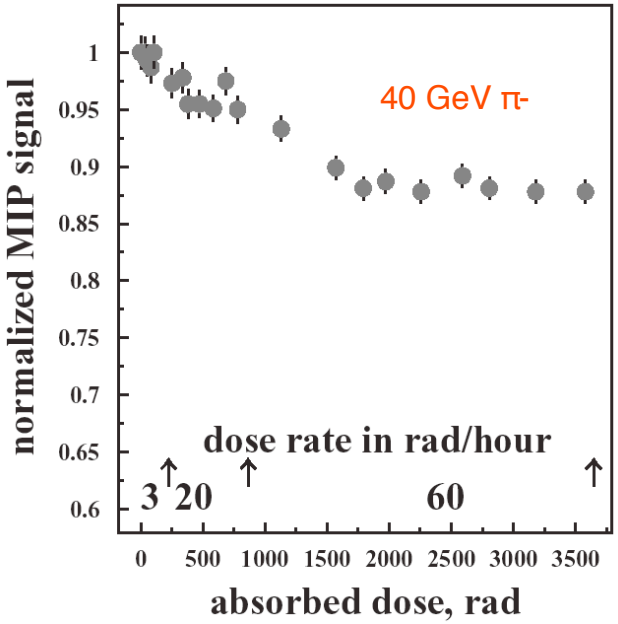
V.Batarin et al, NIM A512 (2003) 488-505, NIM A530 (2004) 286-292

Irradiation studies between 1 and 60 rad/h up to 2 krad





- Signal loss behavior qualitatively similar between electrons and pions
- Damage appears to reach equilibrium at a dose-rate dependent level

Caveat: for the dose-rates used, absorbed doses as can be expected in a HEP experiment were not explored. An additional, specific, possibly cumulative damage from hadrons could not be excluded.

Super-intense hadron beam test of $PbWO_4$ at IHEP

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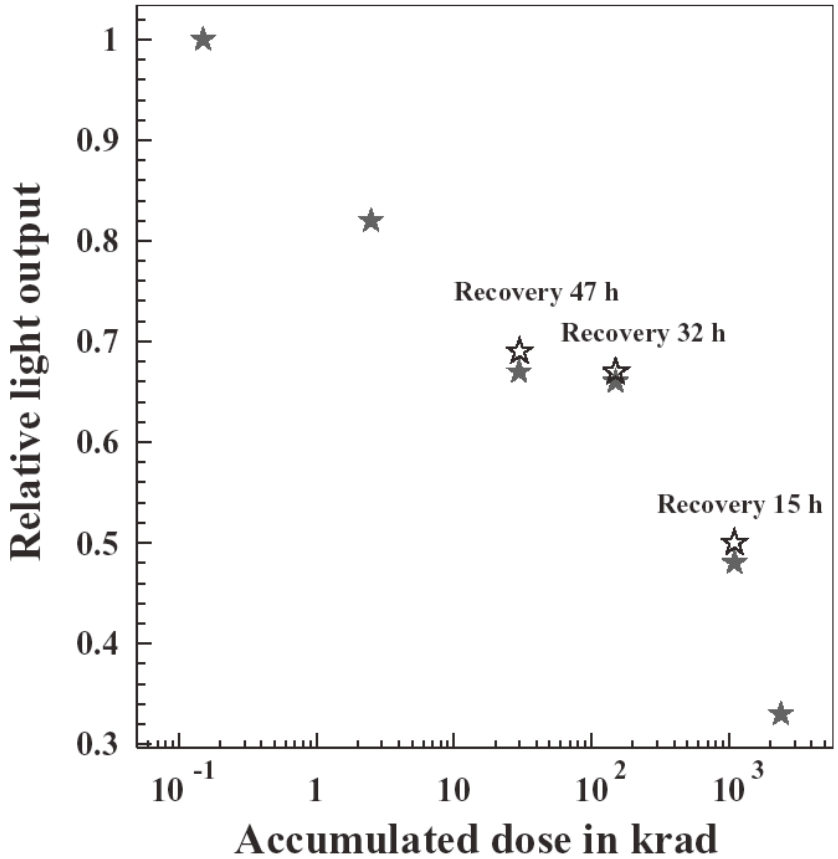
V.Batarin et al, NIM A512 (2003) 488-505

Mixed beam of charged hadrons, neutrons and γ with dose rates of 100 krad/h

- At the constant flux used, the damage appears to be steadily increasing with accumulated dose

- This is unlike pure ionizing radiation damage, which reaches equilibrium at a level depending on dose rate, not beyond what saturation of all color centers can yield

- These measurements hint towards an additional, cumulative, hadron-specific contribution



Proton and γ damage in BGO

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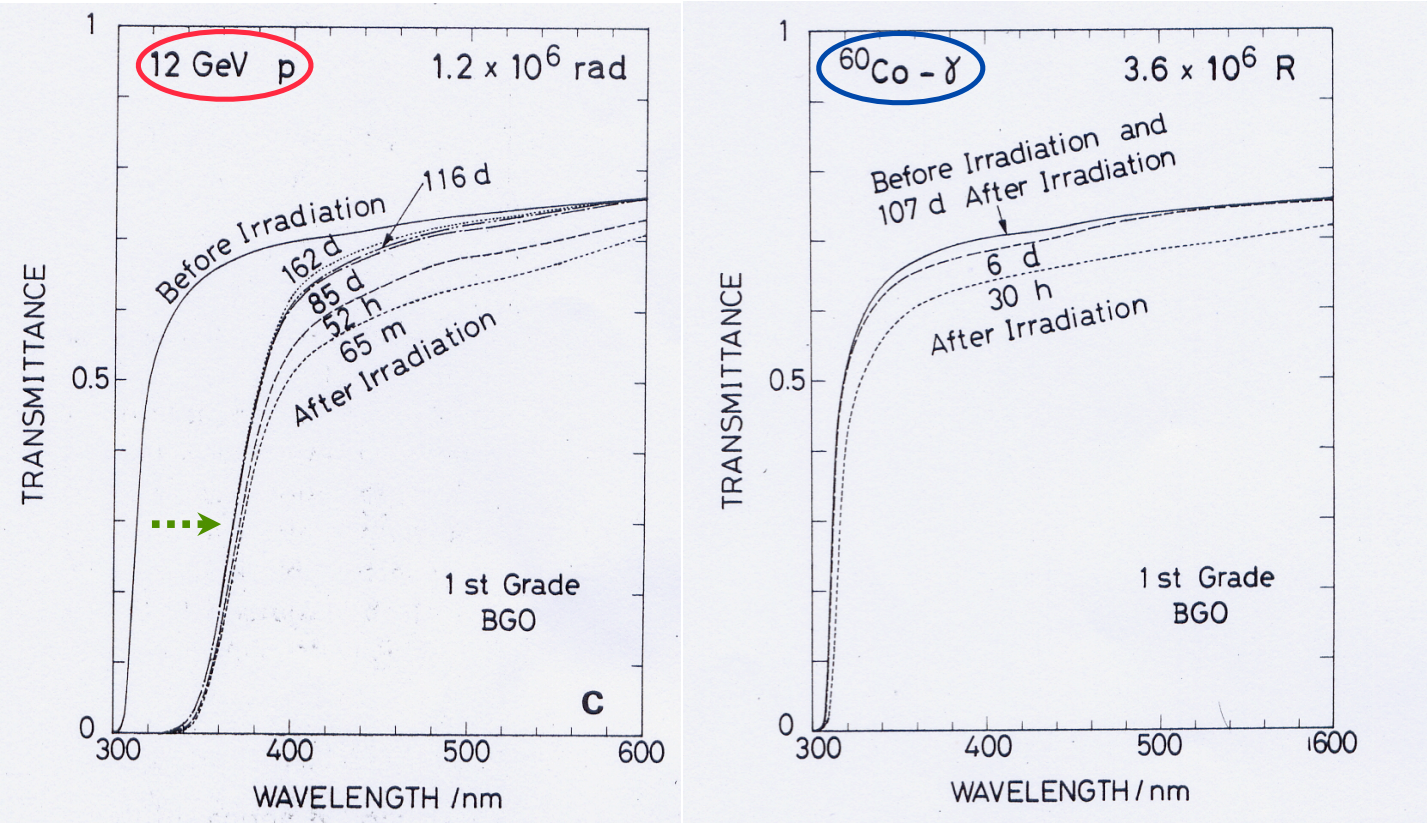

M. Kobayashi et al., NIM 206 (1983) 107-117

- Band-edge shift present for proton-irradiation, which does not recover with time
- No band-edge shift in γ-irradiation

Proton and γ damage in BGO

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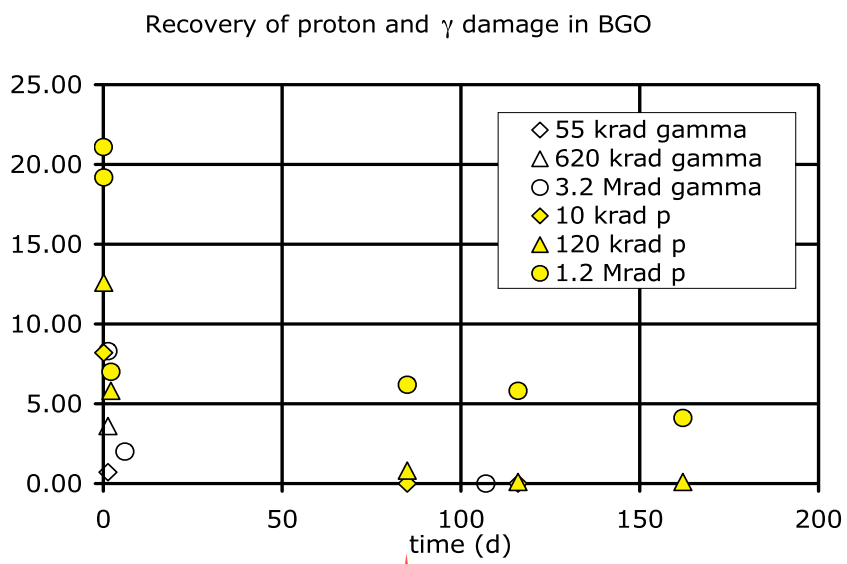
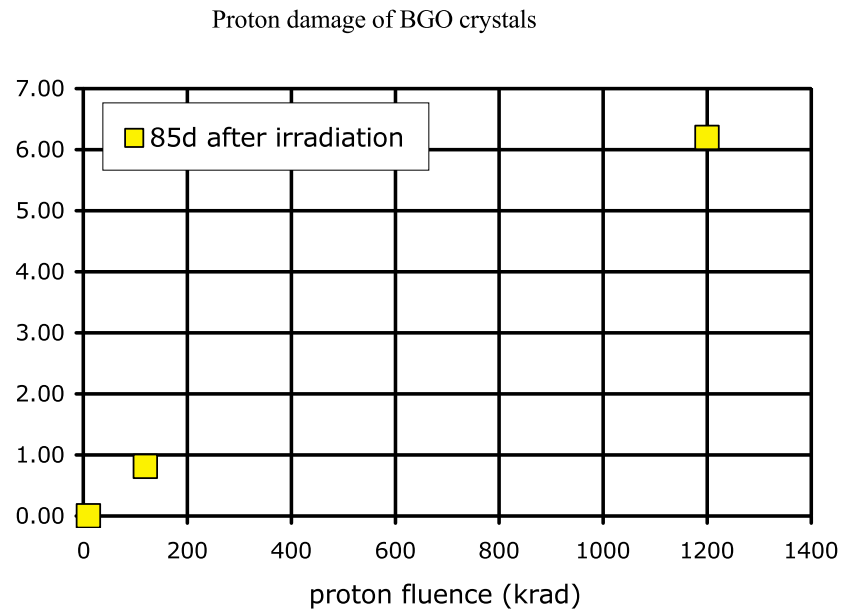
F. Nessi-Tedaldi, Proc. CALOR08, Preprint ETHZ-IPP_PR-2008-04 and arXiv:0807.0693v1
data extracted from M. Kobayashi et al., Nucl. Instr. Meth. 206 (1983) 107-117

Comparison between damage from 12 GeV protons and from γ. Proton flux was given through its corresponding ionizing dose.





Plot damage vs absorbed dose at 85 days

For comparable dose levels, contribution from ionizing radiation small, negligible beyond 80 days.

- Qualitative behavior of proton damage similar to the one in $PbWO_4$

- Proton damage behavior compatible with a linear dependence on proton fluence