Studies of the effect of charged hadrons on Lead Tungstate crystals

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Crystal calorimeters in HEP detector environments are mainly exposed to:

- I - High ionizing radiation levels

- Thoroughly studied, mainly since used for e^+e^- collider experiments
- Growth technology optimized for best performance
- Damage reaches equilibrium at a level that depends on dose rate

- II - High hadron fluxes

- A concern, mainly since chosen for hadron collider experiments
- Discussion of new and older results ➛ focus on $PbWO_4$

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- I - Characteristics of ionizing radiation damage

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R.Y. Zhu, NIM A413(1998) 297-311 & ref. therein

1) Appearance of radiation-induced absorption bands
- Formation of color centers (e- in anion vacancies or holes in cation vacancies)
- Reduction of Light Transmission (LT)
- Possibly loss of uniformity in Light Output

2) Phosphorescence / afterglow
- Noise increase in detected Light

3) No damage in scintillation mechanism (demonstrated in BGO, BaF_2, CsI(Tl), $PbWO_4$)

4) Recovery of damage at room temperature can occur

It depends on crystal type and, within one type, from growth parameters
- Dose rate dependence of damage equilibrium level
- Recovery speed ⇔ depth of traps

Positive consequence:

Ionizing radiation only affects transmission, thus evolution of damage can be monitored through light injection, and corrected for

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?

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

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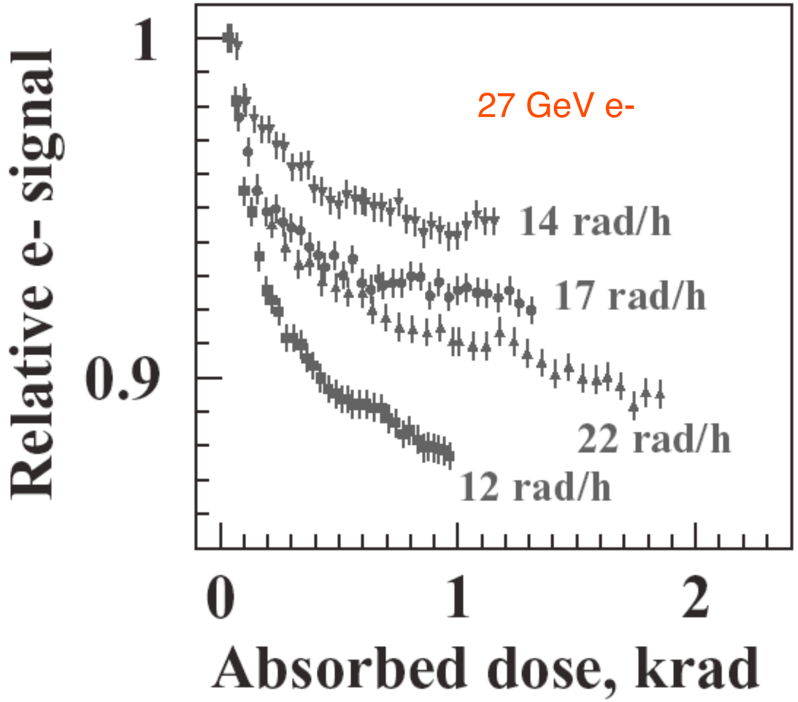
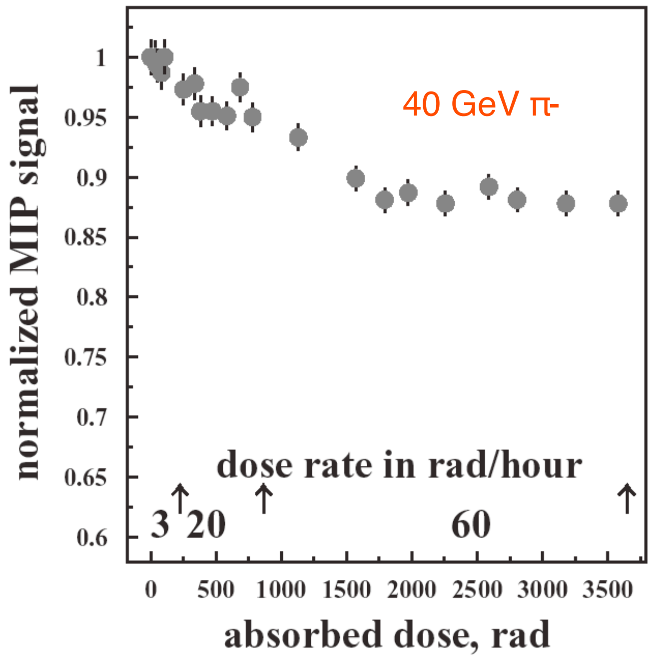
Irradiation studies between 1 and 60 rad/h up to 2 krad

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

V.Batarin et al, Nucl. Instr. Meth. A530 (2004) 286-292





- 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-intensive hadron beam tests of $PbWO_4$ at IHEP

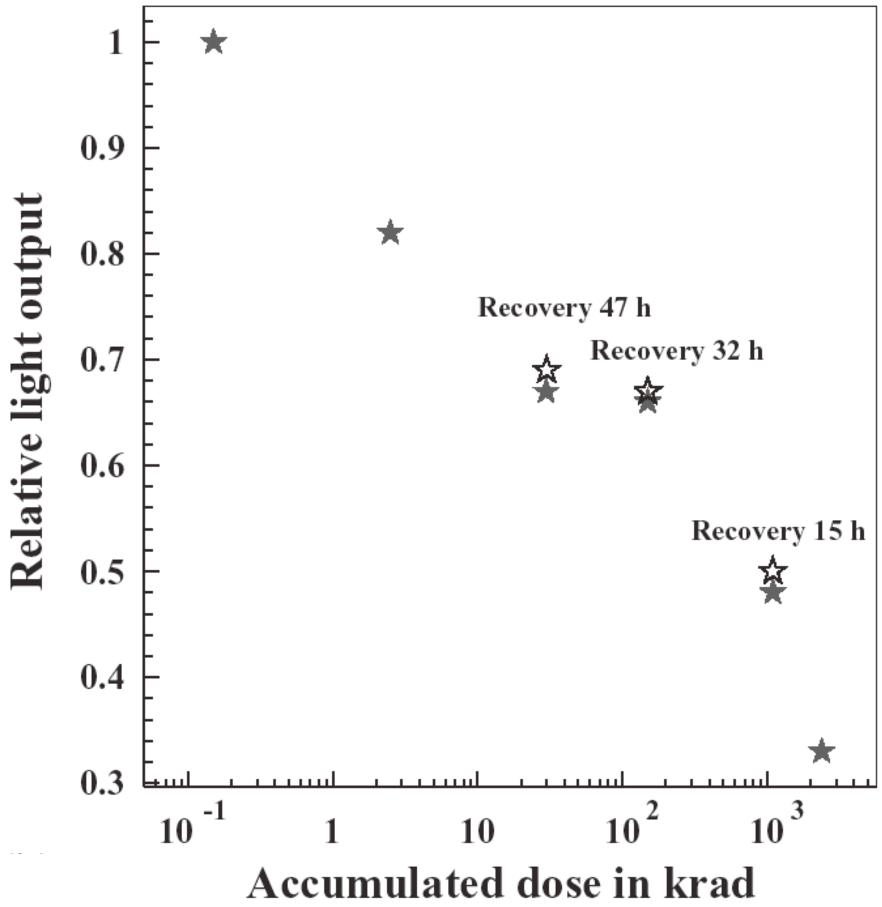
Mixed beam of charged hadrons, neutrons and γ with dose rates of 100 krad/h

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

- 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



Effect on $PbWO_4$ Transmission by 20 GeV/c protons and ^{60}Co γ

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

1) CERN PS T7 beam line, IRRAD1 facility, 20 (24) GeV/c protons

- Flux between $5x10^{11}$ p/cm^2/h and 10^{12} p/cm^2/h* up to various fluences:
  crystals** *a, b, c, d, h*
- Flux of 10^{13} p/cm^2/h up to various fluences:
  crystals** *E, F, G*

2) ENEA Casaccia Calliope ^{60}Co γ irradiation plant

- Dose rate of 1 kGy/h up to various total doses:
  crystals** *t, u, v, w, x, y, z*

Damage measured on:

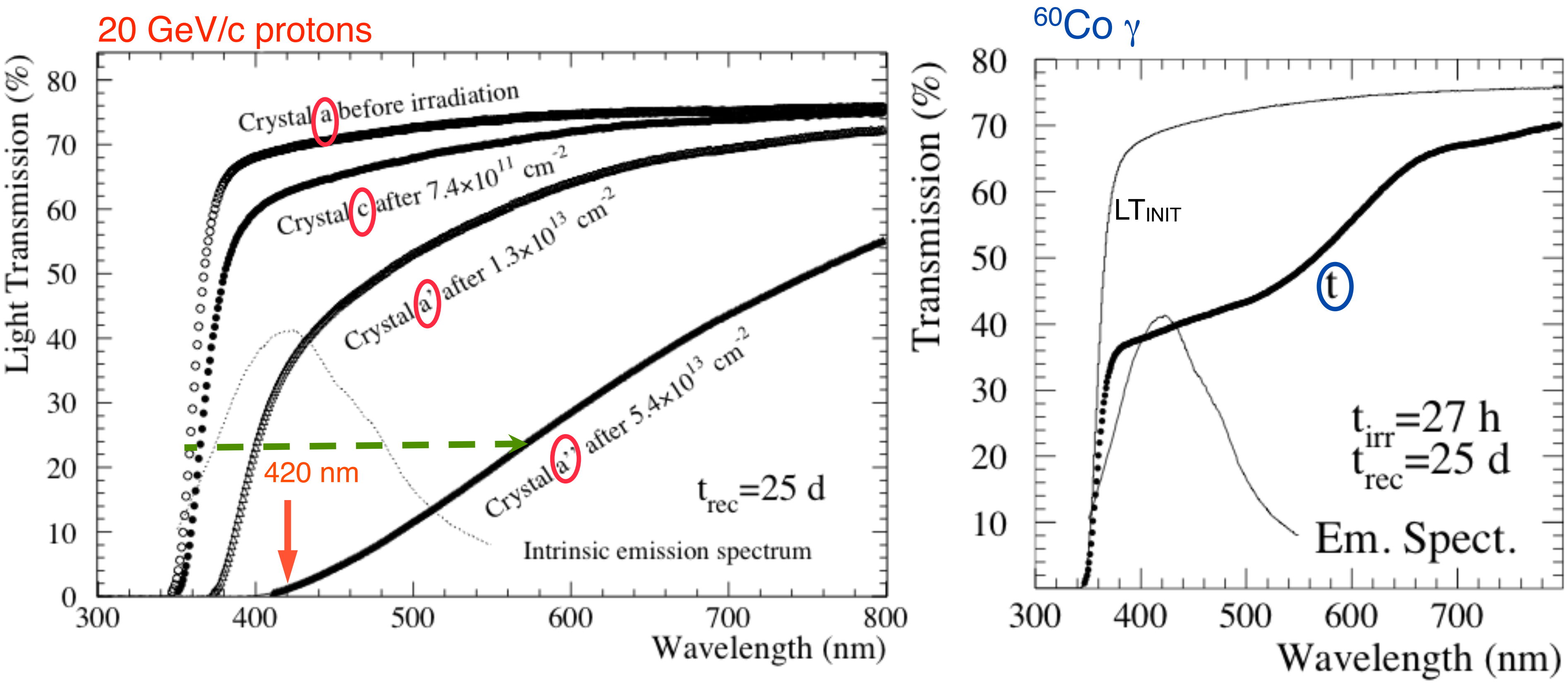
- μ_{IND}, the induced absorption coefficient in Longitudinal Transmission (LT)

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

(*) ionising dose rate equivalent to 1 kGy/h
(**) dimensions 2.4 cm x 2.4 cm x 23 cm

- The damage to Light Transmission as a function of wavelength is qualitatively different between proton - and γ-irradiated crystals

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



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

More features of $PbWO_4$ Transmission after proton and γ irradiation

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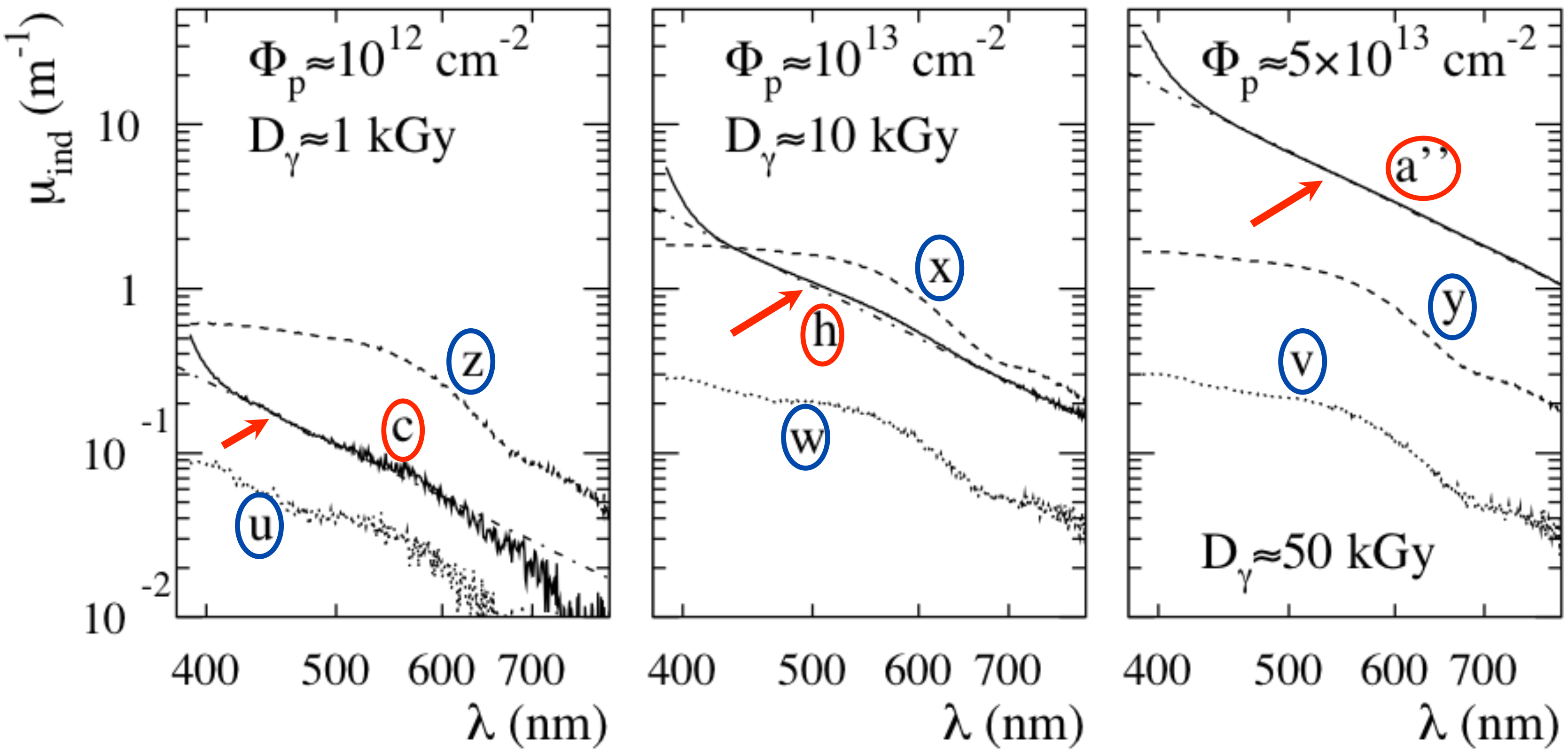
◆ In proton-damaged crystals, Rayleigh-scattering behavior is observed: the scattered light is polarized, and a fit to the data (see below for crystals *a", c, h*) shows

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

◆ not observed for γ-damaged crystals



Transmission recovery in $PbWO_4$

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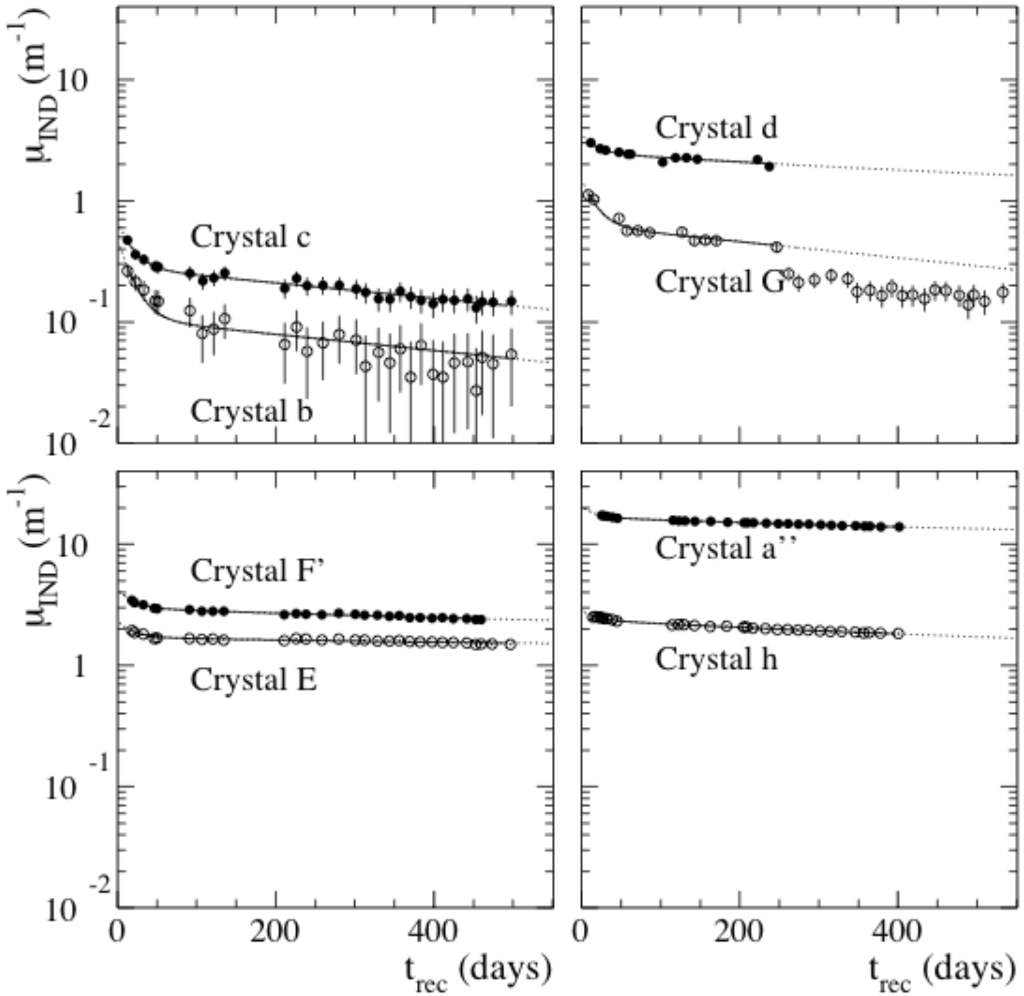
Damage can be globally fitted by $\mu_{IND}(420\ nm, t_{REC}) = \sum_{i=1}^{2} A_i^j e^{-t_{rec}/\tau_i} + A_3^j$
with τ_1 = 17.2 days and τ_2 = 650 days



Proton and γ damage vs. fluence in $PbWO_4$

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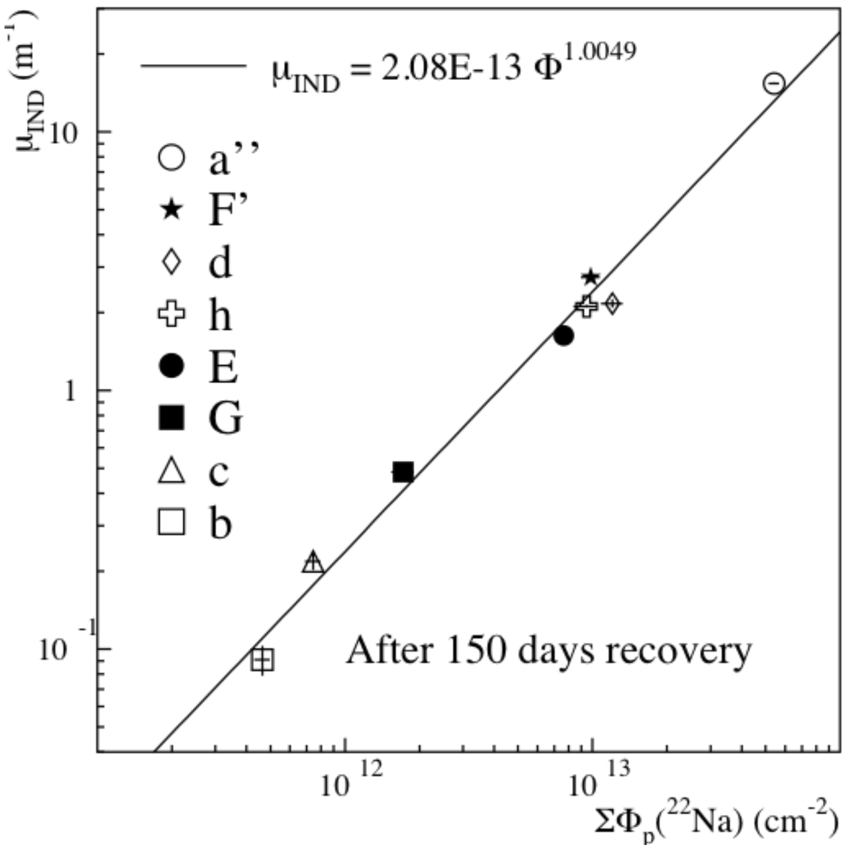
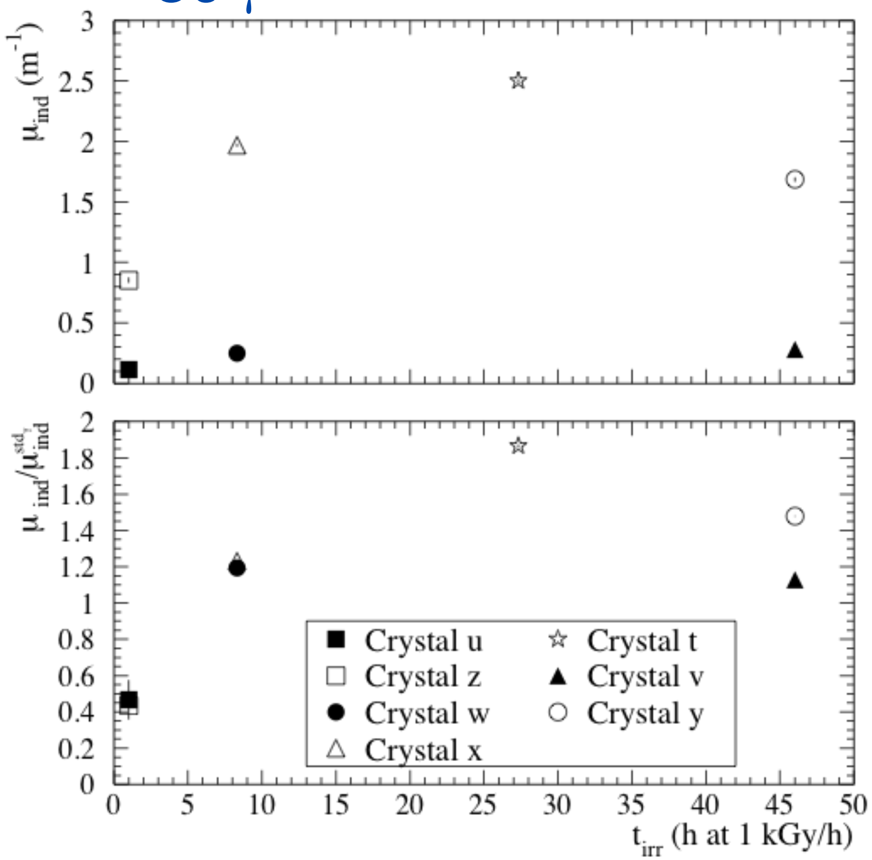
20 GeV/c protons



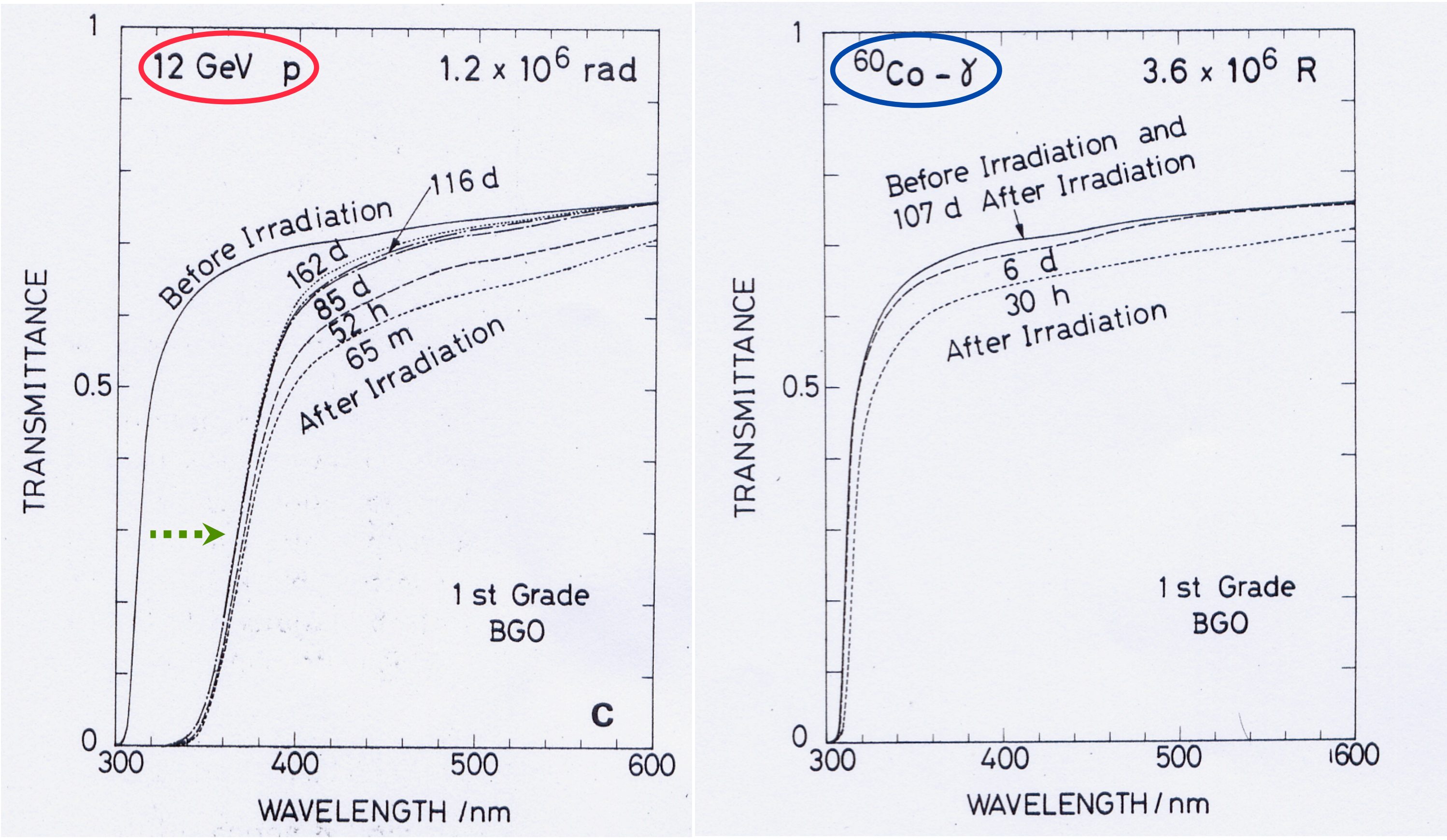
^{60}Co γ



- Proton-induced damage increases linearly with fluence: it has a cumulative effect
- No flux dependence is observed

- γ-induced damage saturates at a value only depending on the initial crystal quality (given by $\mu_{IND}^{\gamma std}$ obtained from a standard quality-assurance γ-irradiation procedure)

Proton and γ damage in BGO



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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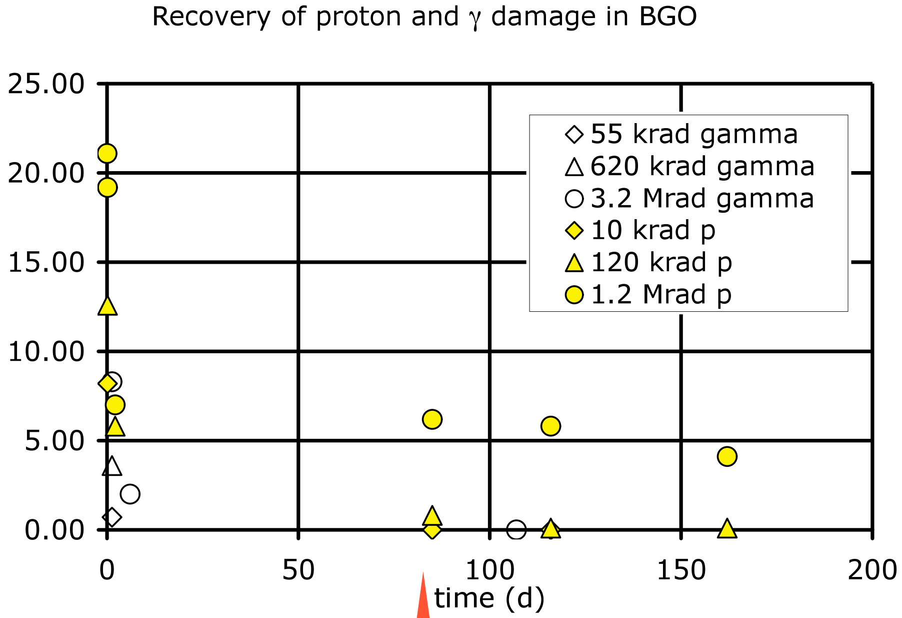
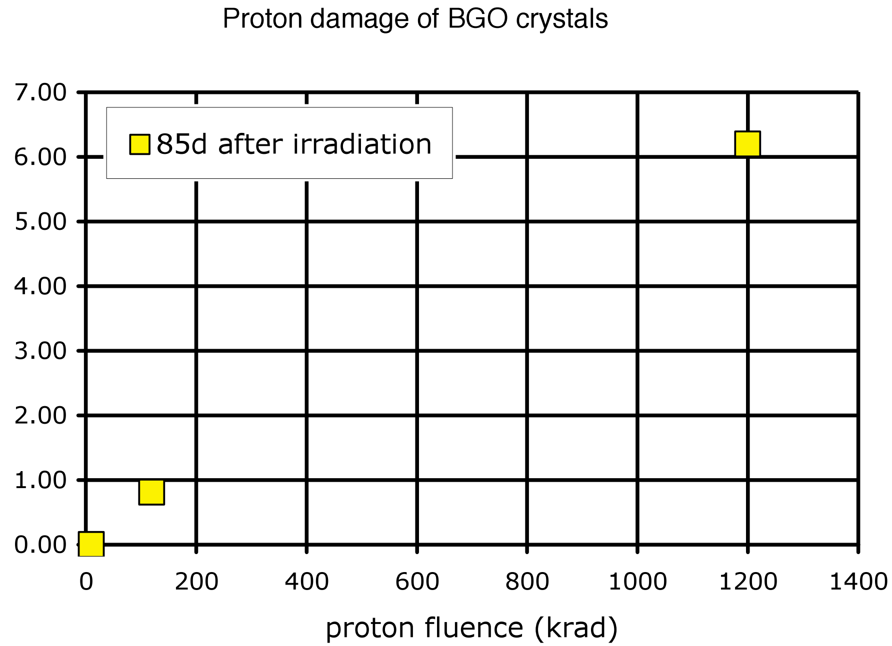
data extracted from M. Kobayashi et al., Nucl. Instr. Meth. 206 (1983) 107-117

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





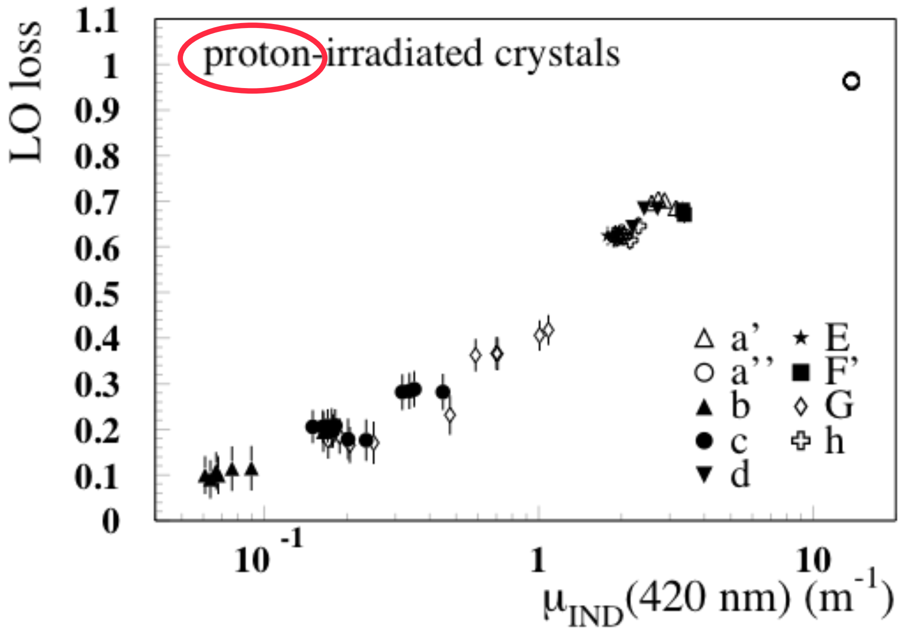
Plot damage vs absorbed dose at 85 days

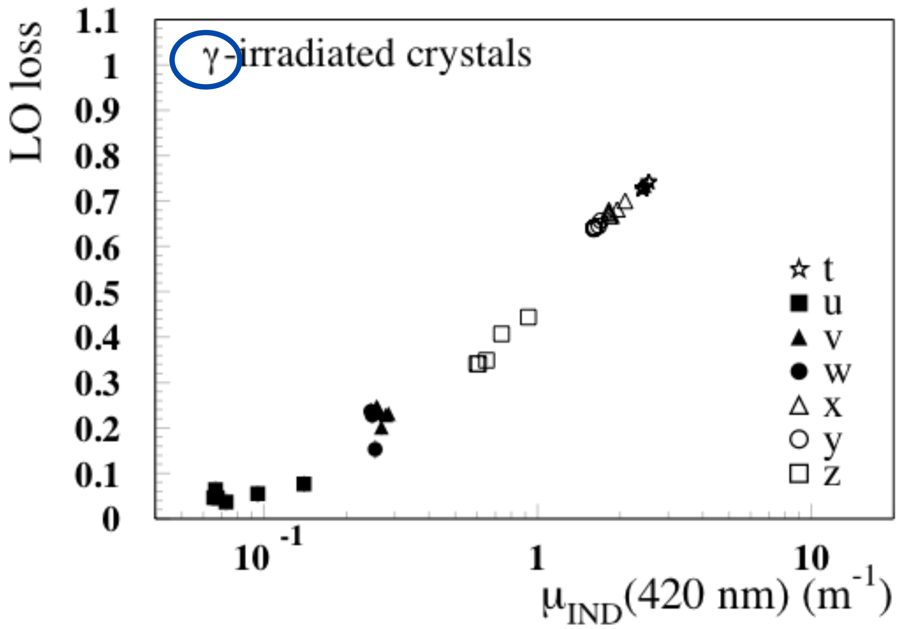
For comparable dose levels, contribution from ionizing radiation small, negligible beyond 80 days.

- Qualitative behavior of proton damage similar to the one in $PbWO_4$
- Proton damage behavior compatible with a linear dependence on proton fluence

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

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





- 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 accuracy of the measurement, the two correlations are compatible

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

Understanding of hadron damage mechanism in $PbWO_4$

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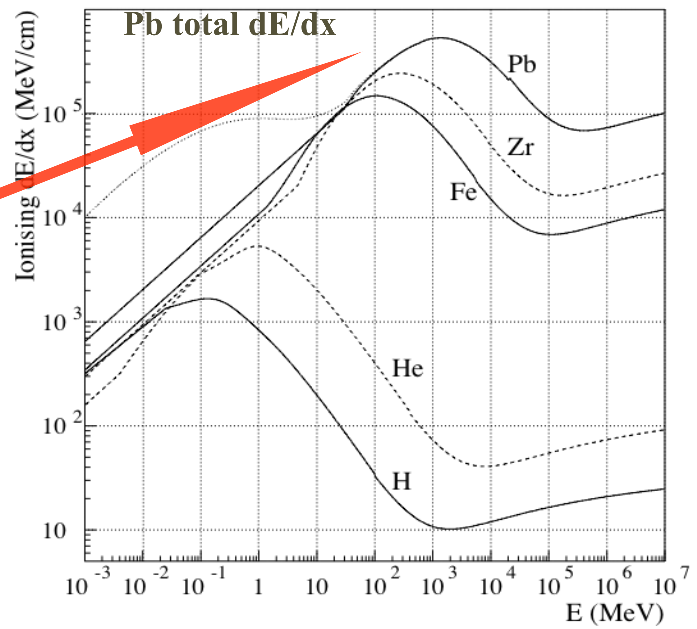
Specific features of proton damage:

- It grows linearly with fluence
- It only affects Light Transmission, and can thus be monitored
- The scintillation mechanism is not altered
- 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



Comparison between proton and pion damage in $PbWO_4$

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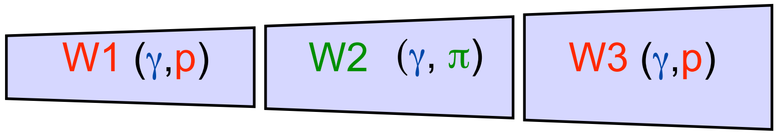
P.Lecomte, D.Luckey, F.Nessi-Tedaldi, F.Pauss, D.Renker, Nucl. Instr. Meth. A587 (2008) 266-271

Hadron fluxes at 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, tested with γ in May 2004, was cut into 3 sections, W1, W2 and W3. The γ damage was annealed by heating.

✓ W1 and W3 were irradiated with 24 GeV/c protons at the CERN PS in Fall 2004.
✓ W2 was irradiated with 290 MeV/c π^+ in the πE1 beam line at PSI (Villigen) in August 2005.

Light Transmission changes in $PbWO_4$: pions versus protons

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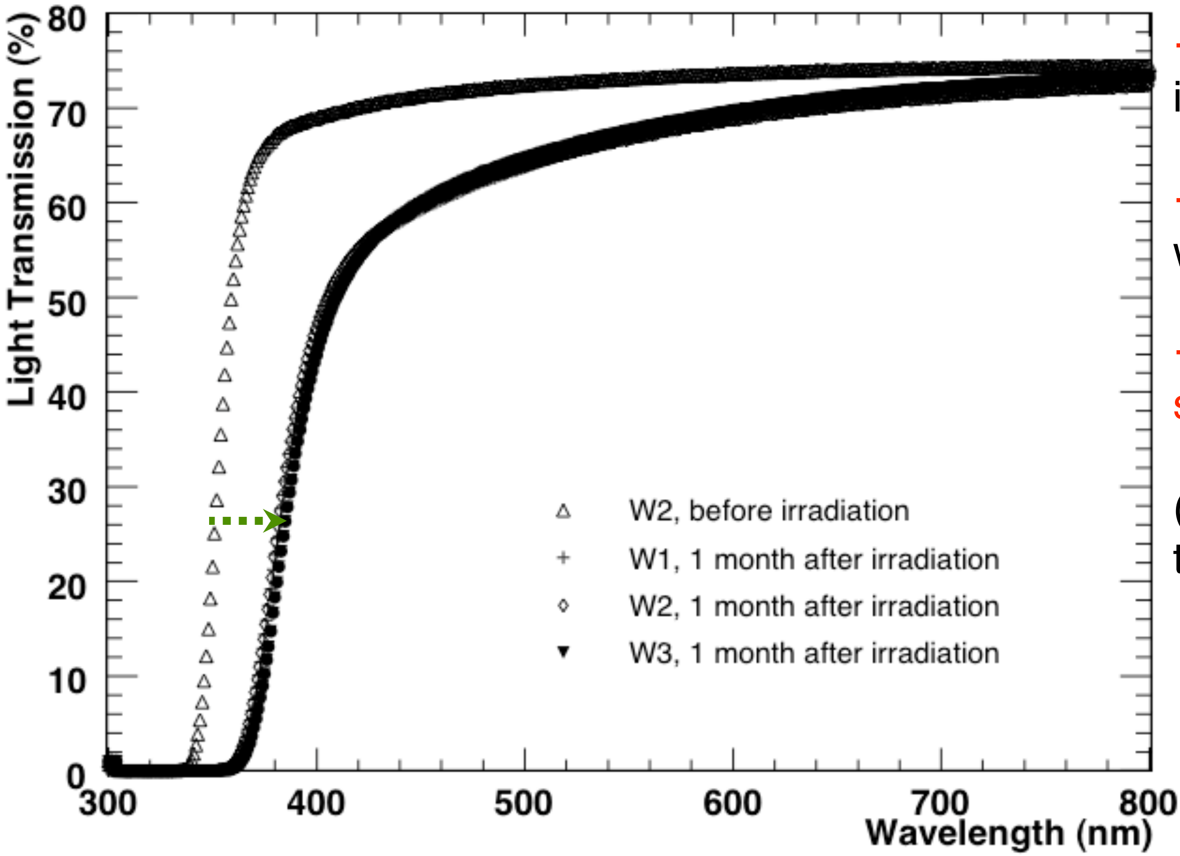
$\Phi_p = (1.17 \pm 0.11) \times 10^{13}$ p/cm^2 with W1 and W3 placed one in front of the other during irradiation

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



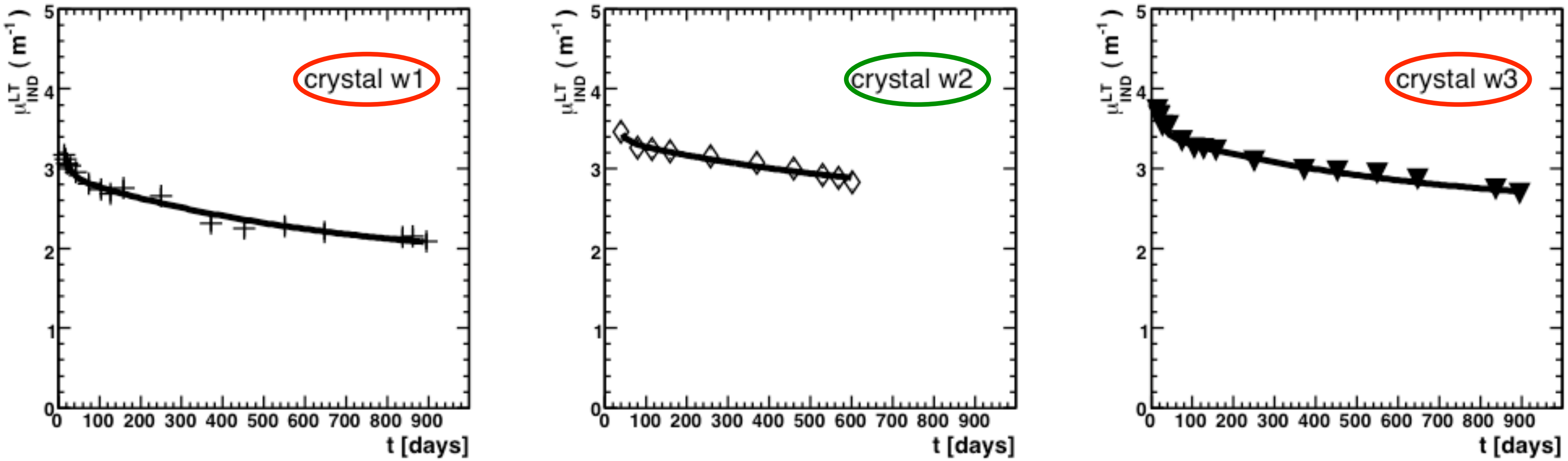
→ LT shape similar after p and π irradiations

→ Band-edge shift present for π as well

→ p and π damage qualitatively similar

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

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



Damage profile in $PbWO_4$: Transverse Transmission

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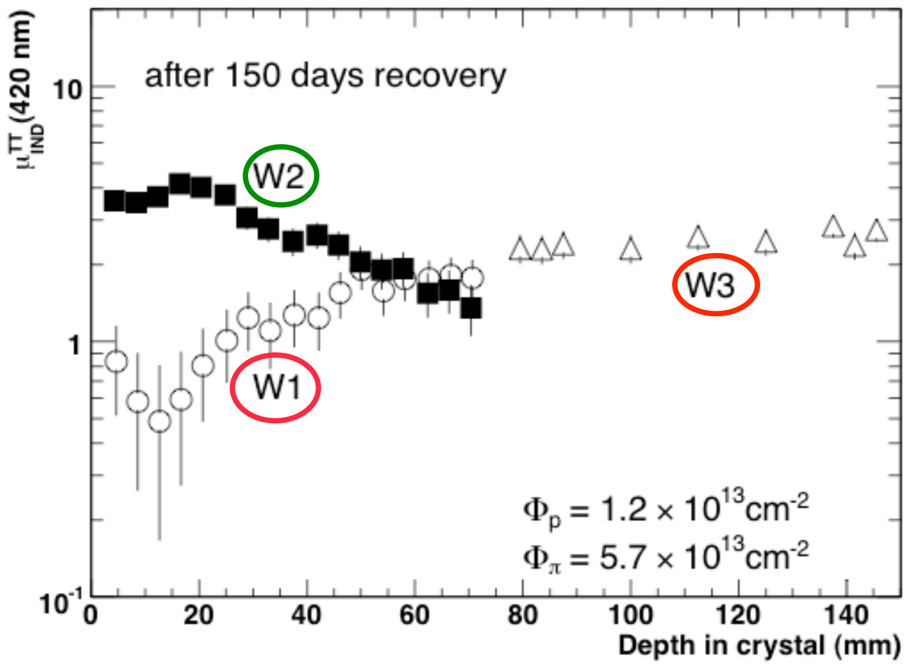
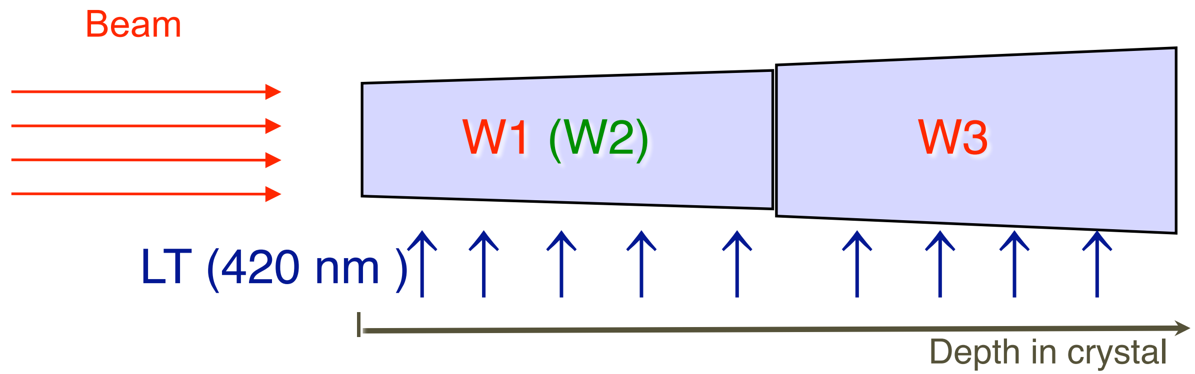
Pion damage along crystal length is highest right after entrance into the crystal, then drops due to pion absorption, as expected

Proton damage raises and then stays high.

(Large uncertainties at crystal entrance for W1 due to small damage and difficulty to measure next to crystal extremity)





Comparison to FLUKA Monte Carlo for $PbWO_4$

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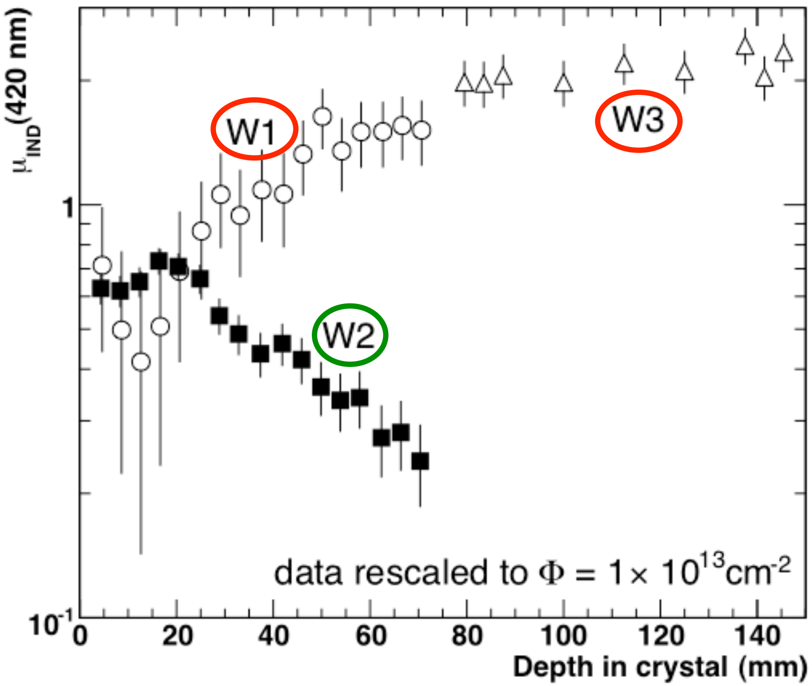
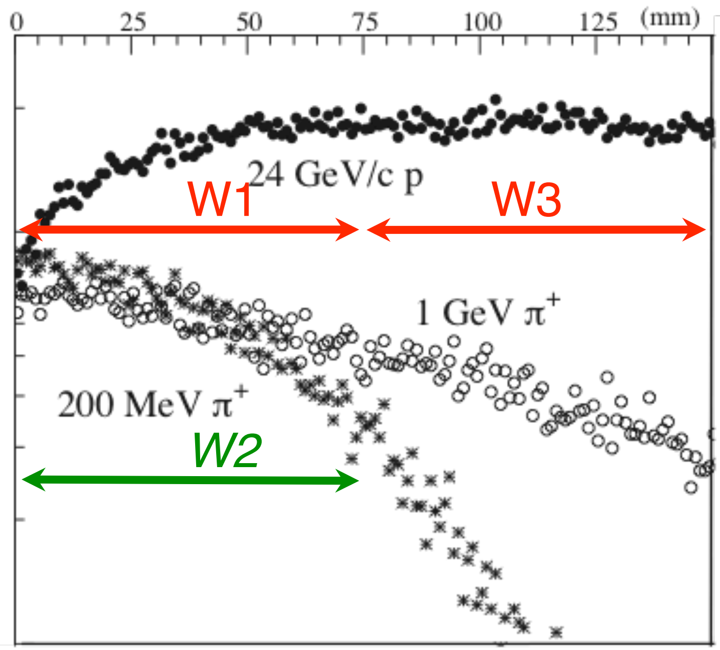
measured induced absorption coefficients



Star density profiles from FLUKA simulation



M. Huhtinen, XPG meeting 25-MAR-03

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

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

Star density ratios as the scaling factor in $PbWO_4$?

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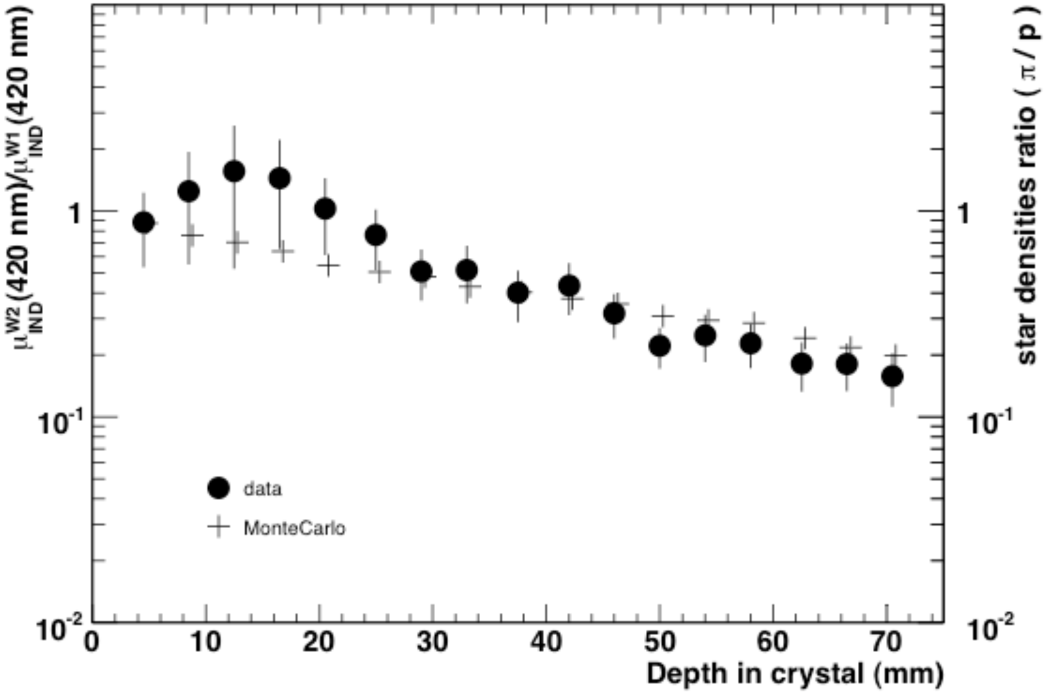
Compare the profiles of pion-to-proton induced absorption coefficient ratios

with

the profile of pion-to-proton star densities ratios from FLUKA simulations

The two ratio profiles agree within the accuracy of the data

→ scaling of damage is determined by the ratio of star densities



Recipe: 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

Conclusions

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- A hadron-specific, cumulative damage from charged hadrons has been observed in tests on BGO and $PbWO_4$. 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 accuracy 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 have allowed to establish that the damage scales with the density of stars from FLUKA simulations. The results can thus be used to estimate the expected damage for different experimental conditions.

- Since the damage mechanism above should be absent for crystals with elements below Z=71, a hadron damage test in such crystals should confirm the present understanding of damage mechanisms.


By the way: the lizard’s blue color is due to Rayleigh scattering ...