Comparison of Radiation Damages Induced by Ionization dose and Neutrons in BaF_2 Crystals

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October 8, 2015

High Dose Irradiation at JPL TID Facility

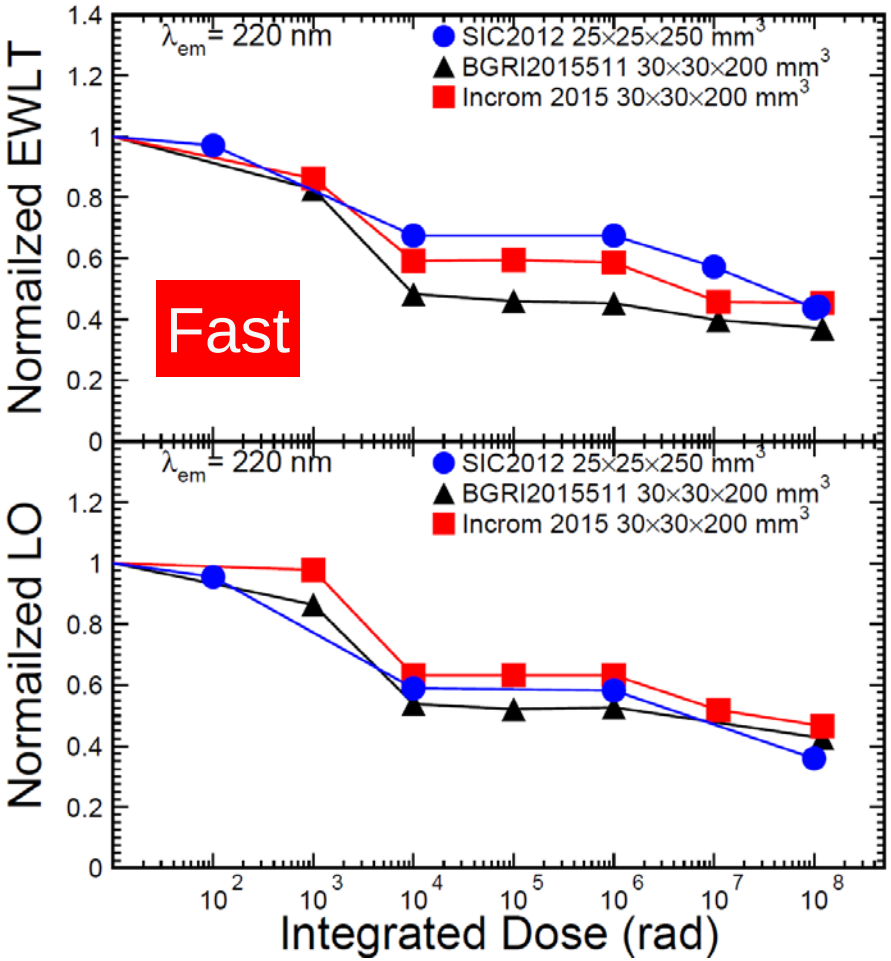
ID	Dimension (mm^3)
BaF_2 Incrom 2	**30x30x200**
Capillary S093	134
Capillary S097	134
30 BOET LFS Plates	14x14x1.5
LFS BOET	25x25x180
LSO CTI	25x25x200
LYSO SIPAT	25x25x200
BaF_2 BGRI511	**30x30x200**

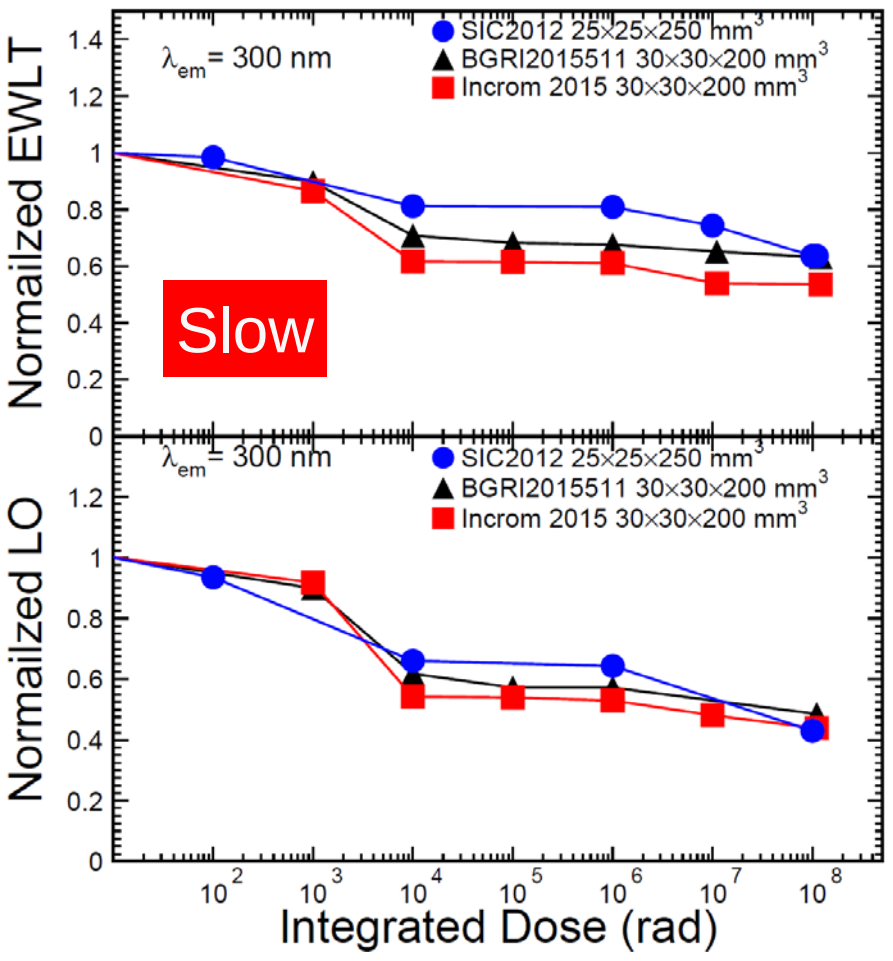
Experiments

- Co-60 sources with dose up to 120 Mrad at a dose rate of 0.8 Mrad/h;
- Crystal properties measured at room temperature : LT, LO & LRU;
- BaF_2 LO measurement: PMT R2059, Na-22 Coincidence Trigger, Two layers of Tyvek and Grease coupling.

γ-ray Induced Damage in BaF_2

Consistent radiation hardness in crystals from three vendors





BaF2 crystals are radiation hard up to 120 Mrad

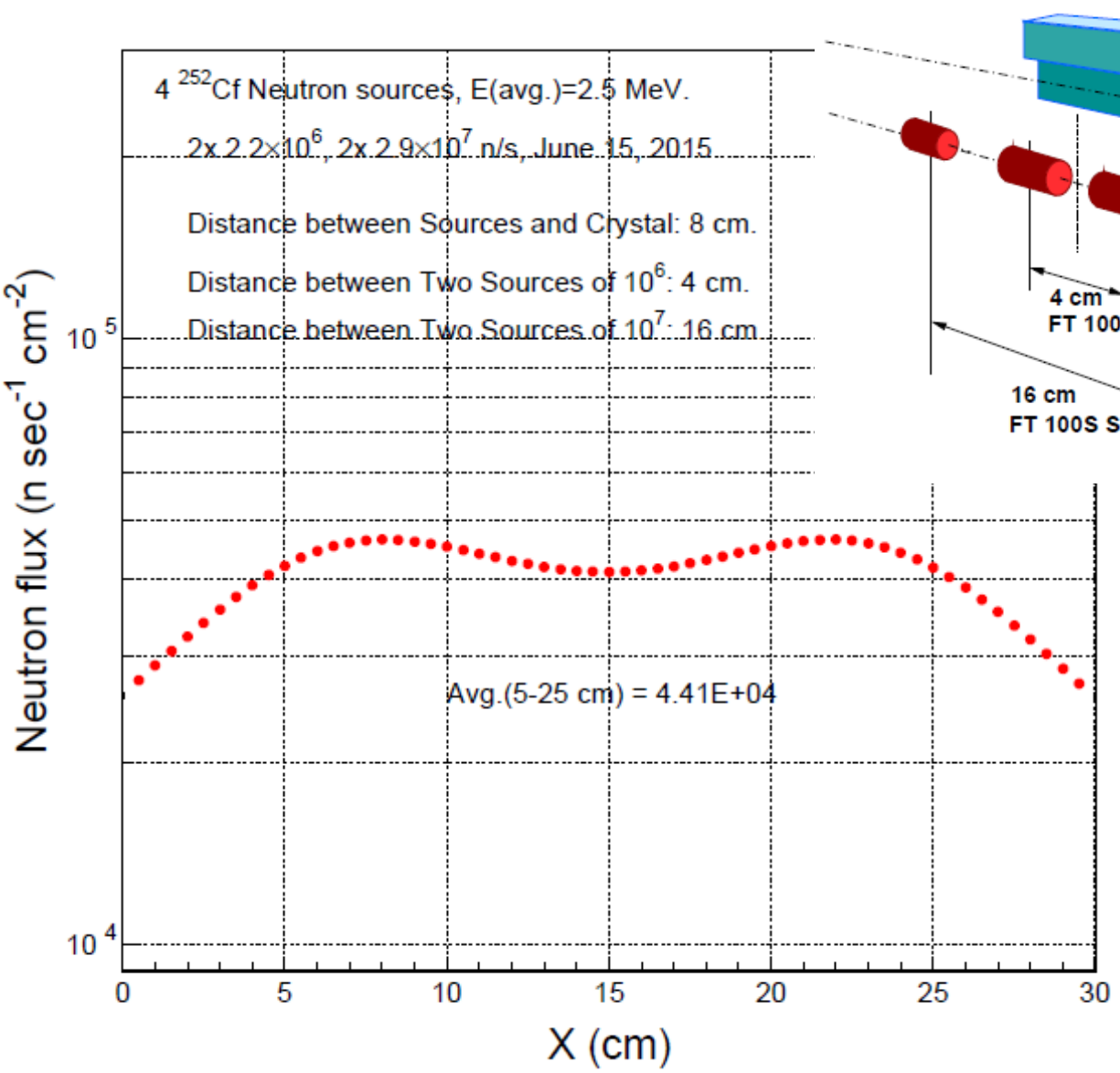
BaF_2 Samples Irradiated by Cf-252

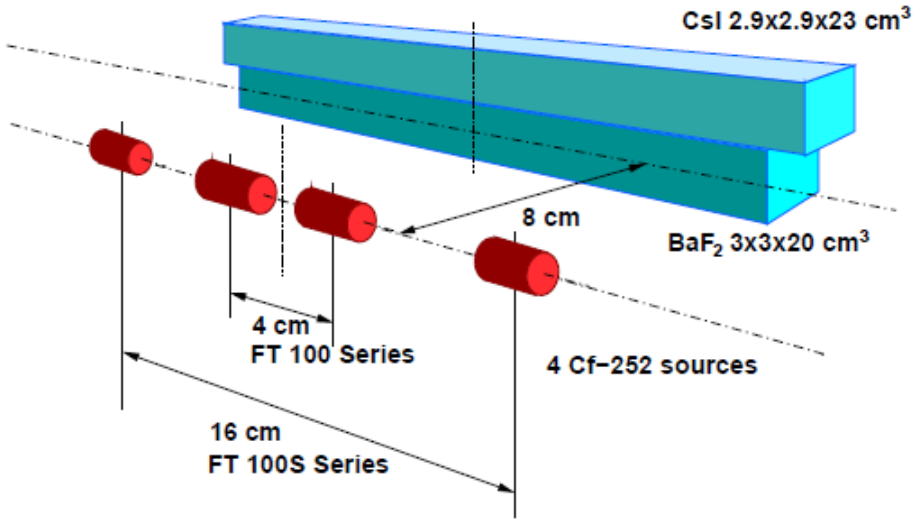
ID	Dimension (mm^3)	Polishing
BaF_2 SIC-1	30x30x250	All faces
BaF2 Incrom 2	30x30x200	All faces
BaF2 Incrom 3	30x30x200	All faces

Experiments

- Irradiation to 1.1 x 10^{11} n/cm^2 by 2.5 MeV neutrons with a flux of 4.4 x 10^4 n/s/cm^2;
- Properties measured at room temperature : LT, PHS, LO & LRU
- BaF_2 LO measurement: PMT R2059, Na-22 Coincidence Trigger, Two layers of Tyvek and Grease coupling.

Two Cf-252 Neutron Sours Pairs

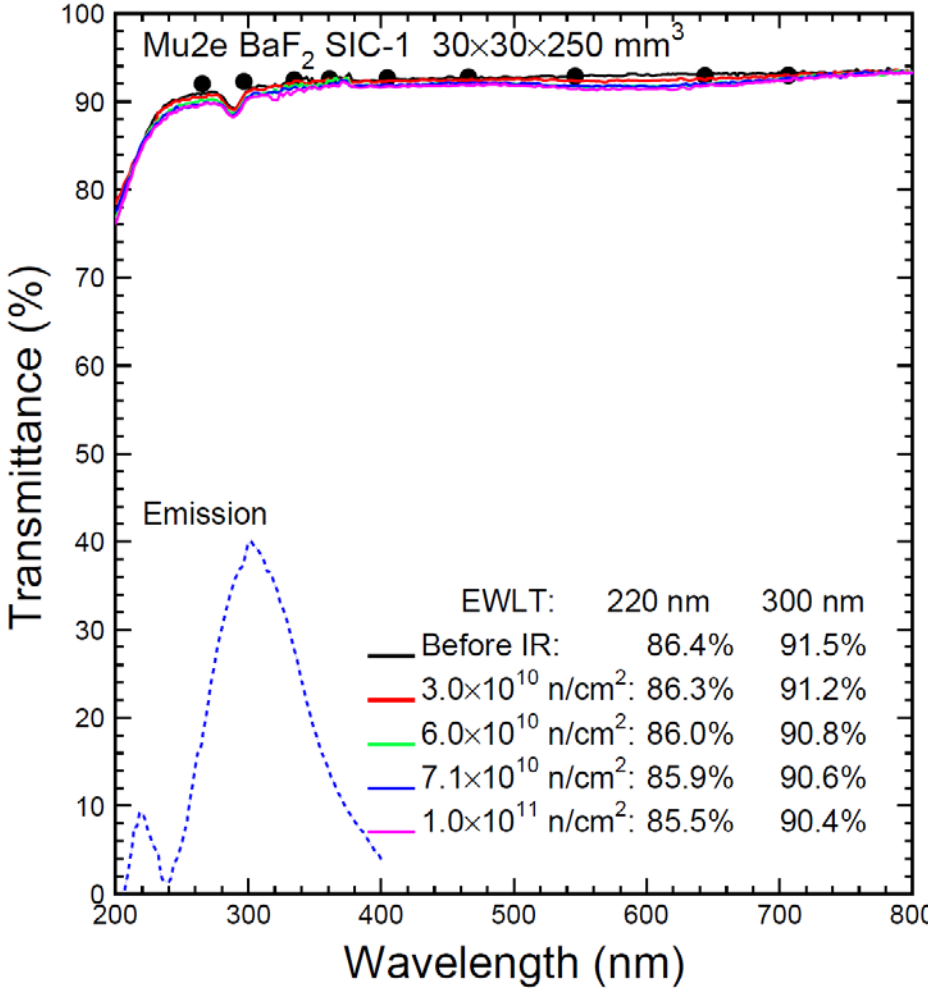


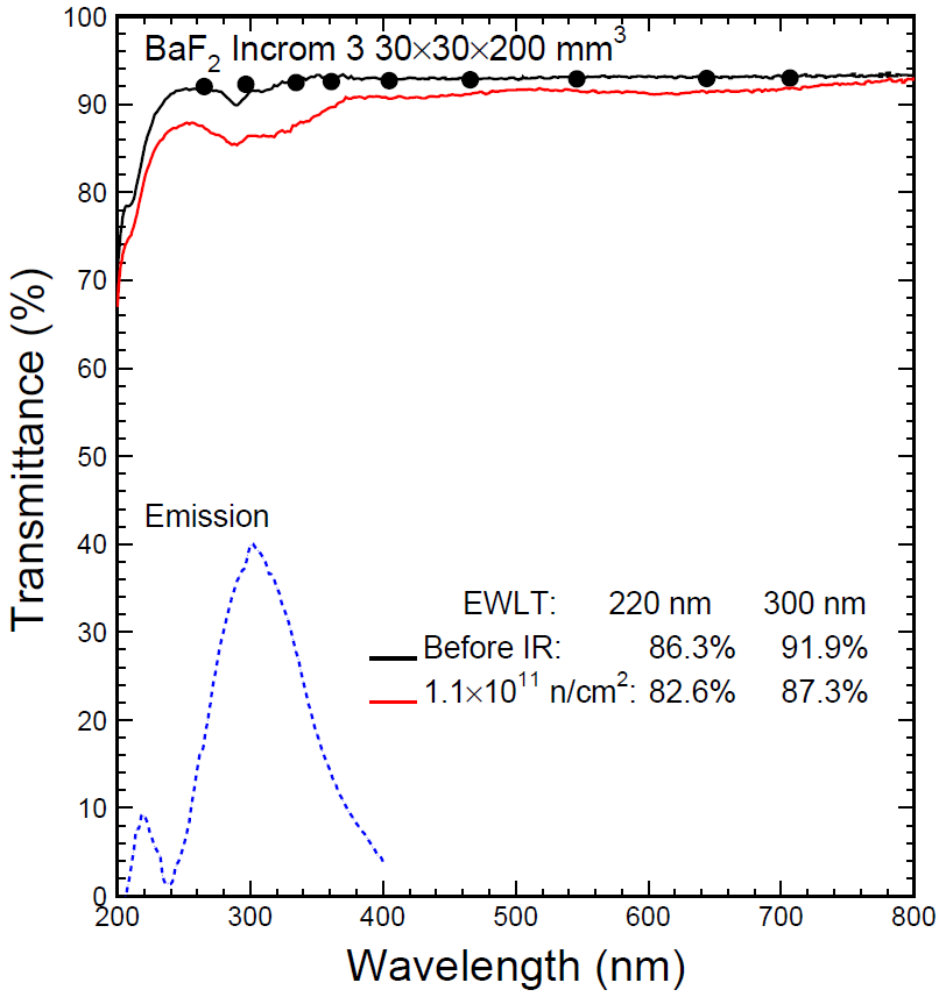


One each of BaF_2 and CsI samples were irradiated to 1.1 x 10^{11} n/cm^2 by 2.5 MeV neutrons from two pairs of Cf-252 sources with a flux of 4.4 x 10^4 n/s/cm^2. An SIC BaF_2 sample was irradiated in 2014 to 1 x 10^{11} n/cm^2.

Small LT Loss in BaF_2 Samples

After 10^{11} n/cm^2: effect in optical quality is small

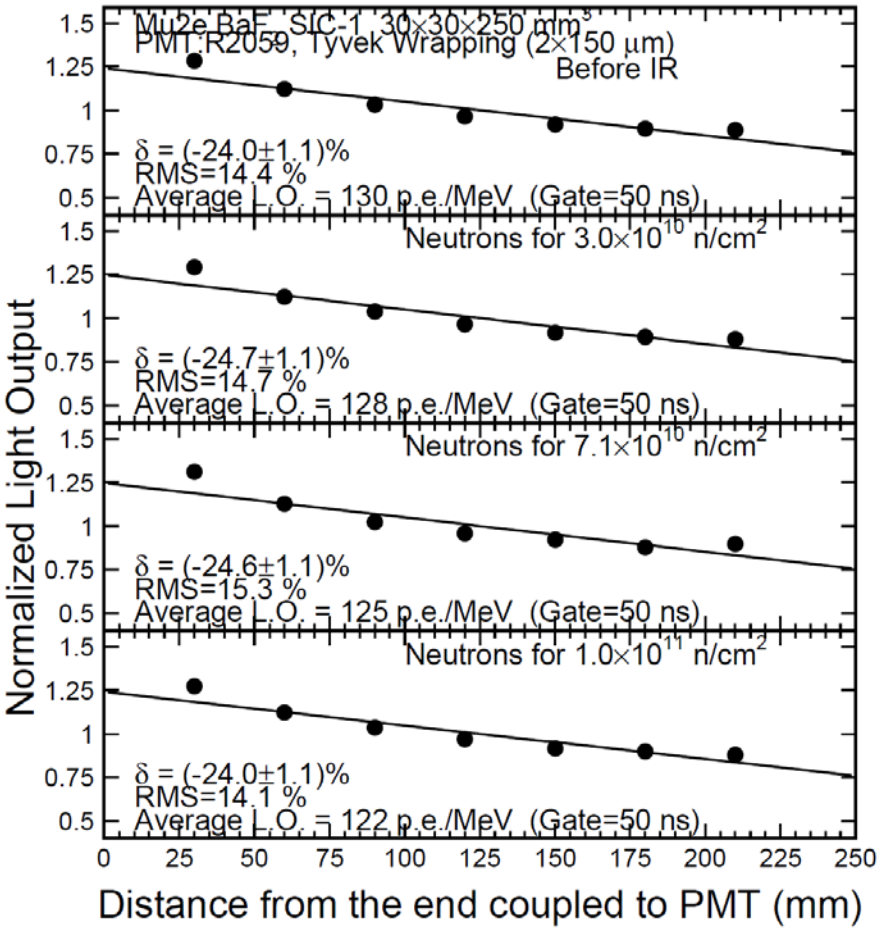


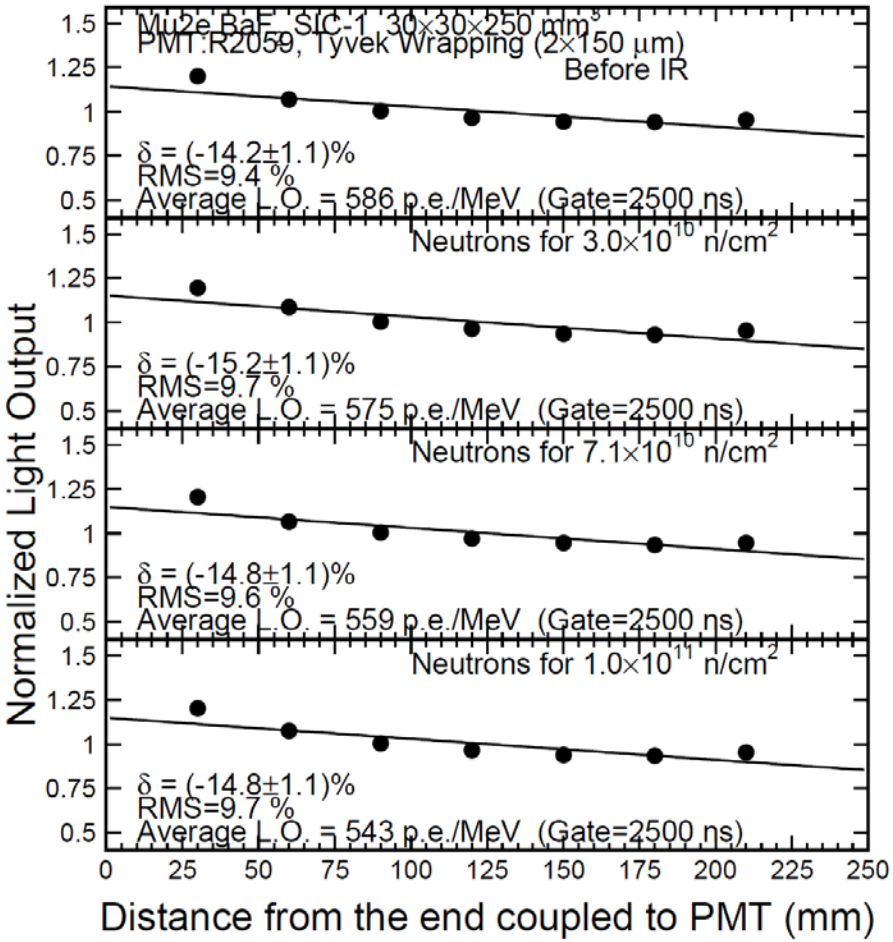


LO & LRU: SIC-1

50 ns: 130 to 122 p.e./MeV

2.5 μs: 586 to 543 p.e./MeV

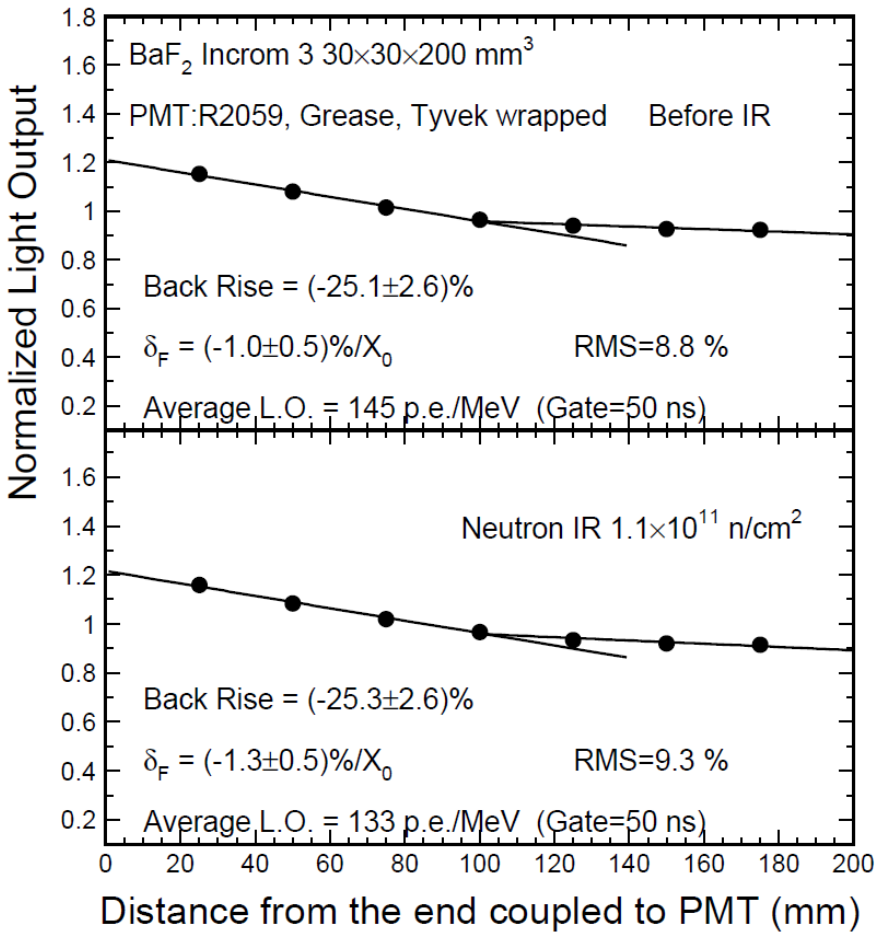


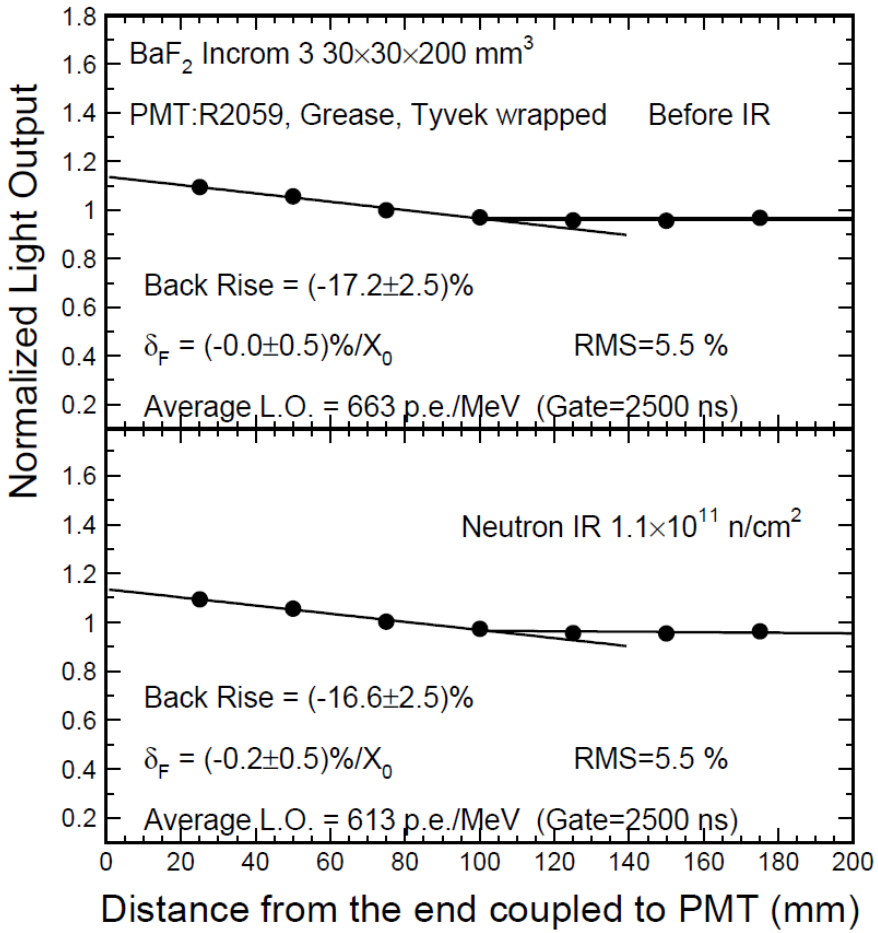


LO & LRU: Incrom 3

50 ns: 145 to 133 p.e./MeV

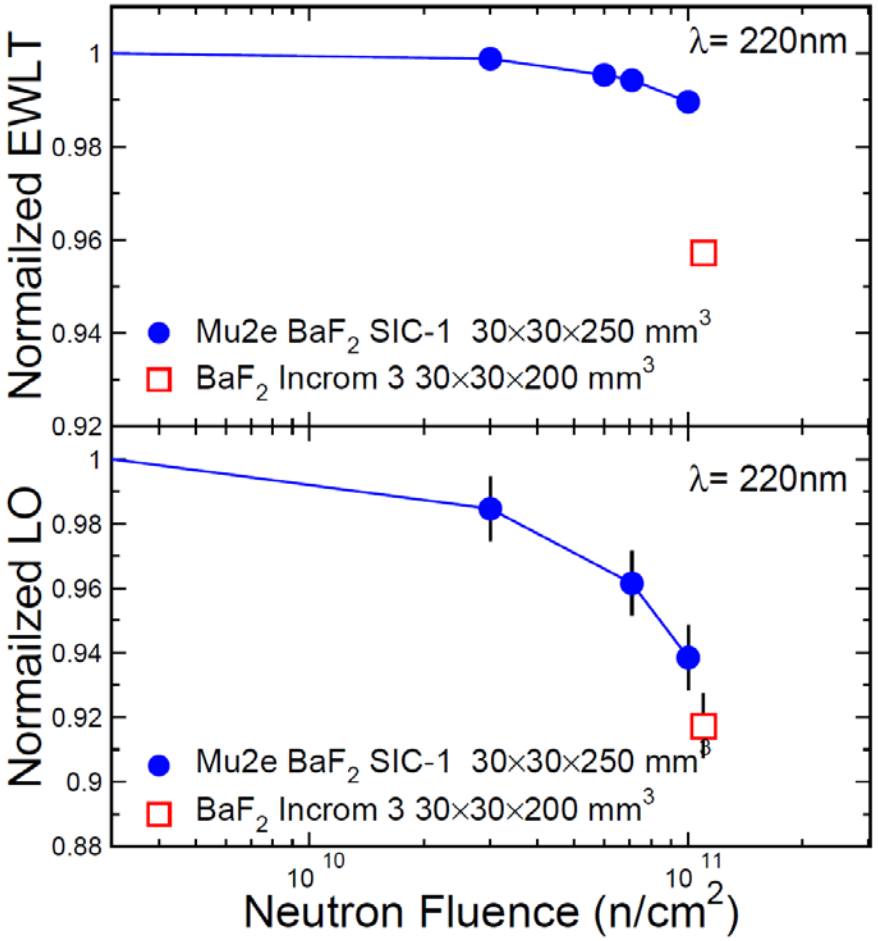
2.5 μs: 663 to 613 p.e./MeV

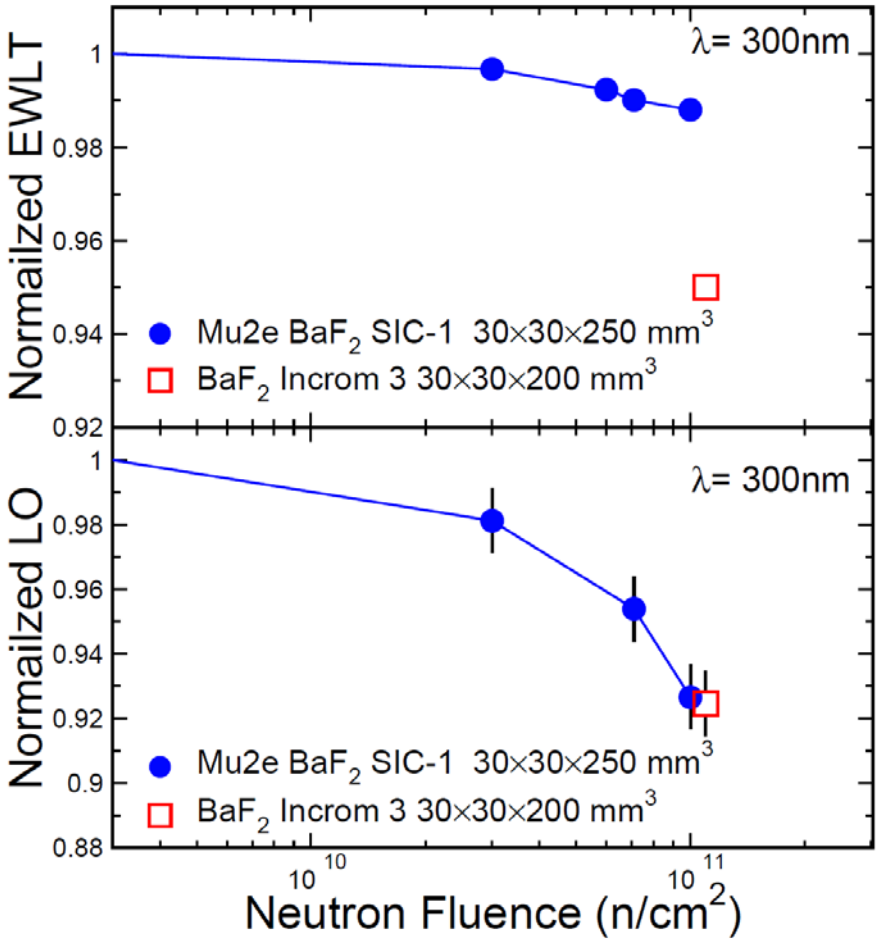




Normalized EWLT & LO

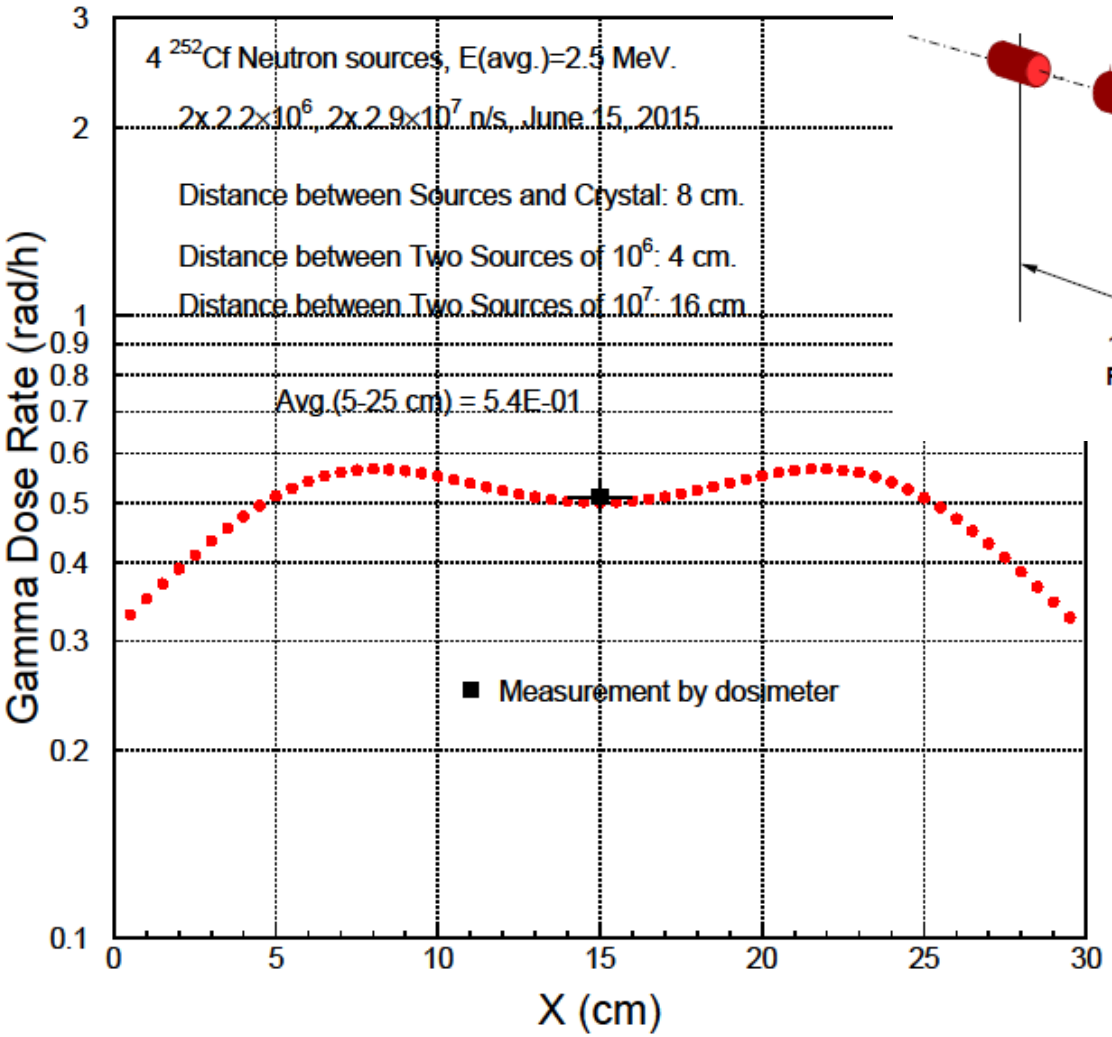
Consistent LO losses observed between SIC and Incrom samples

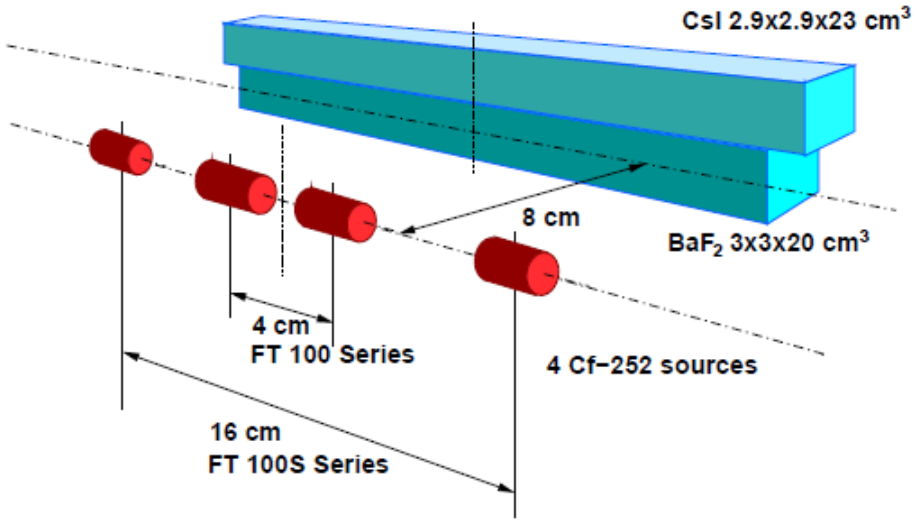




Cf-252 source is known to have ɣ-ray background, but **how much**?

γ-Ray Background from Cf-252



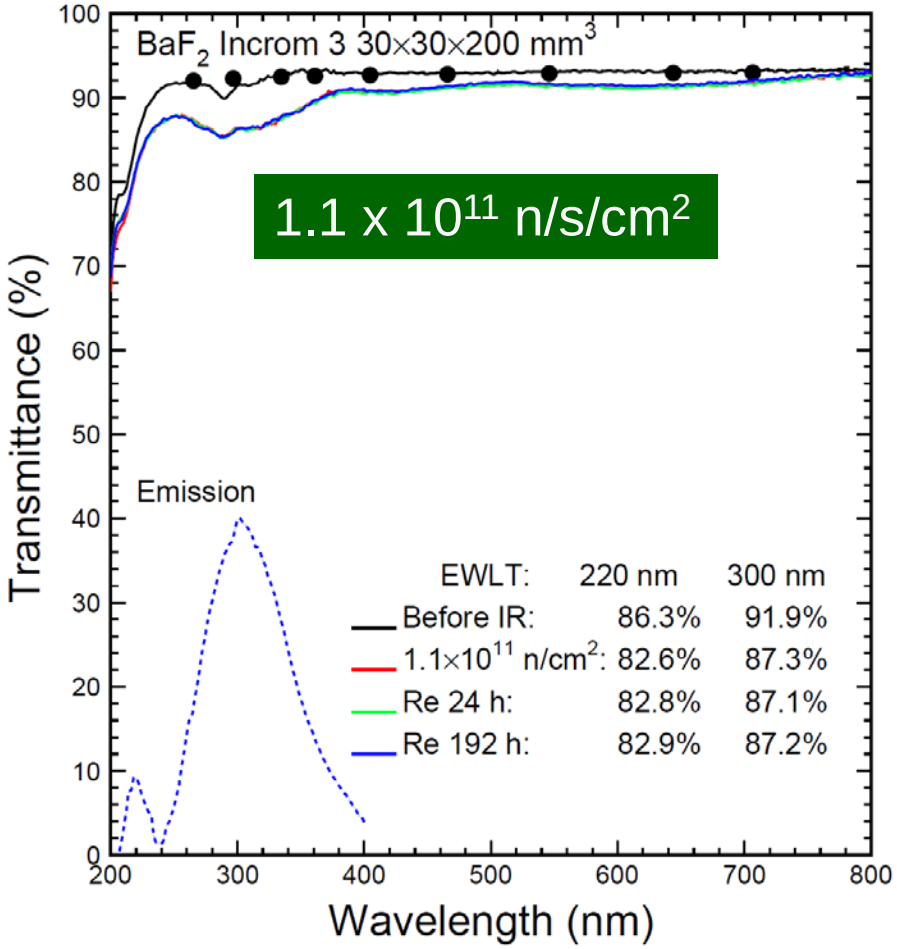


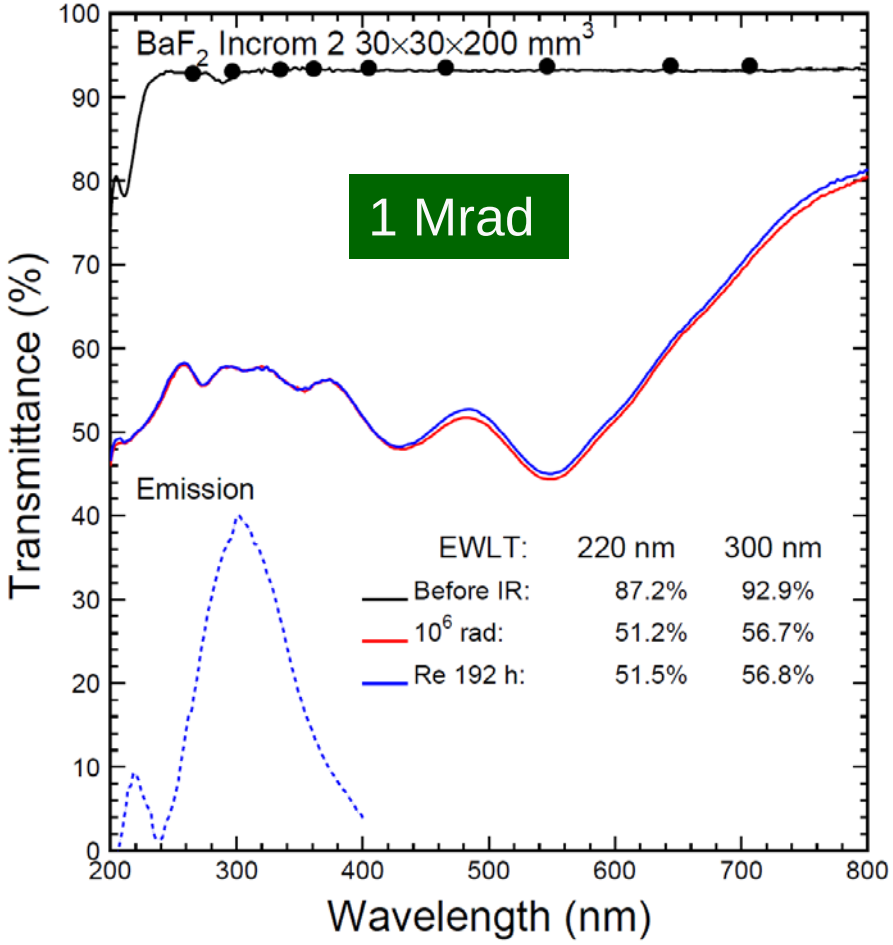
γ-ray dose rate: 0.54 rad/h, measured by a dosimeter Radcal 9010 and 9060/10x5-60, is consistent with reference [1]. The corresponding dose is 360 rad for 1.1 x 10^{11} n/cm^2.

[1] R. Martin et.al., "Production, Distribution and Application of Californium-252 Neutron Sources", presented in IRRMA'99, North Carolina, 1999

Recovery of BaF_2 after Irradiations

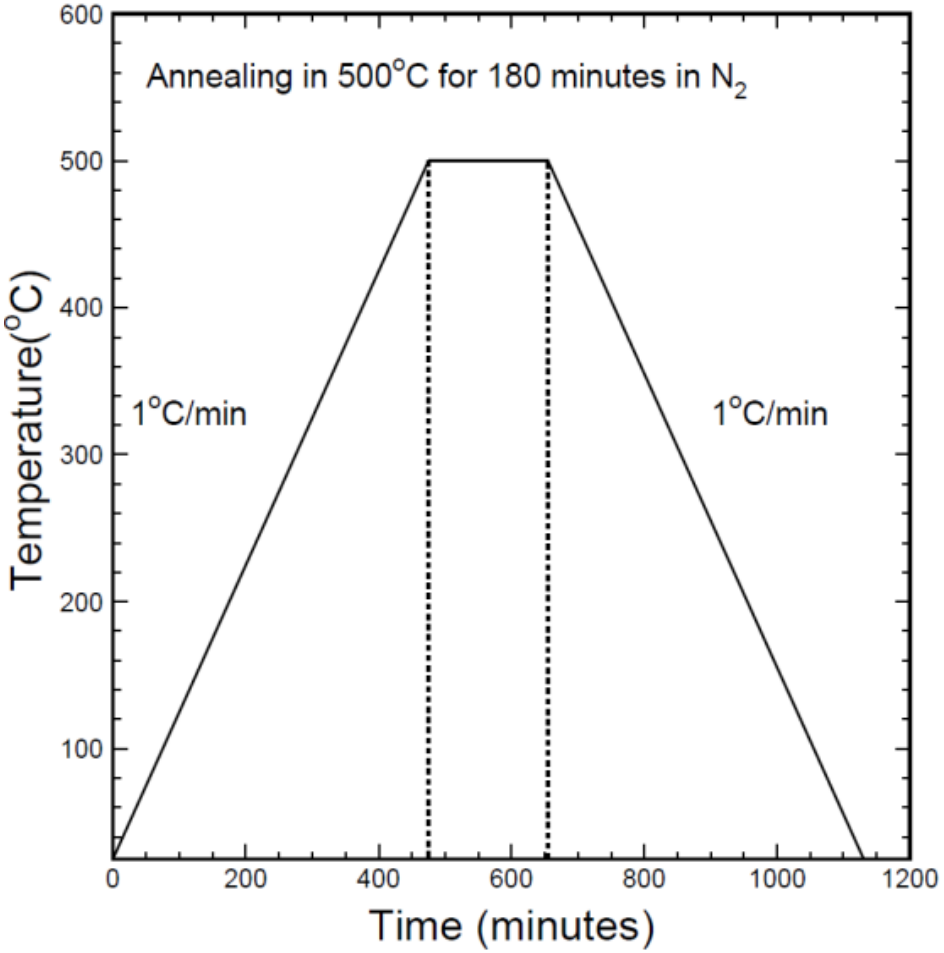
No recovery in transmittance after irradiations by both ɣ-rays and neutrons

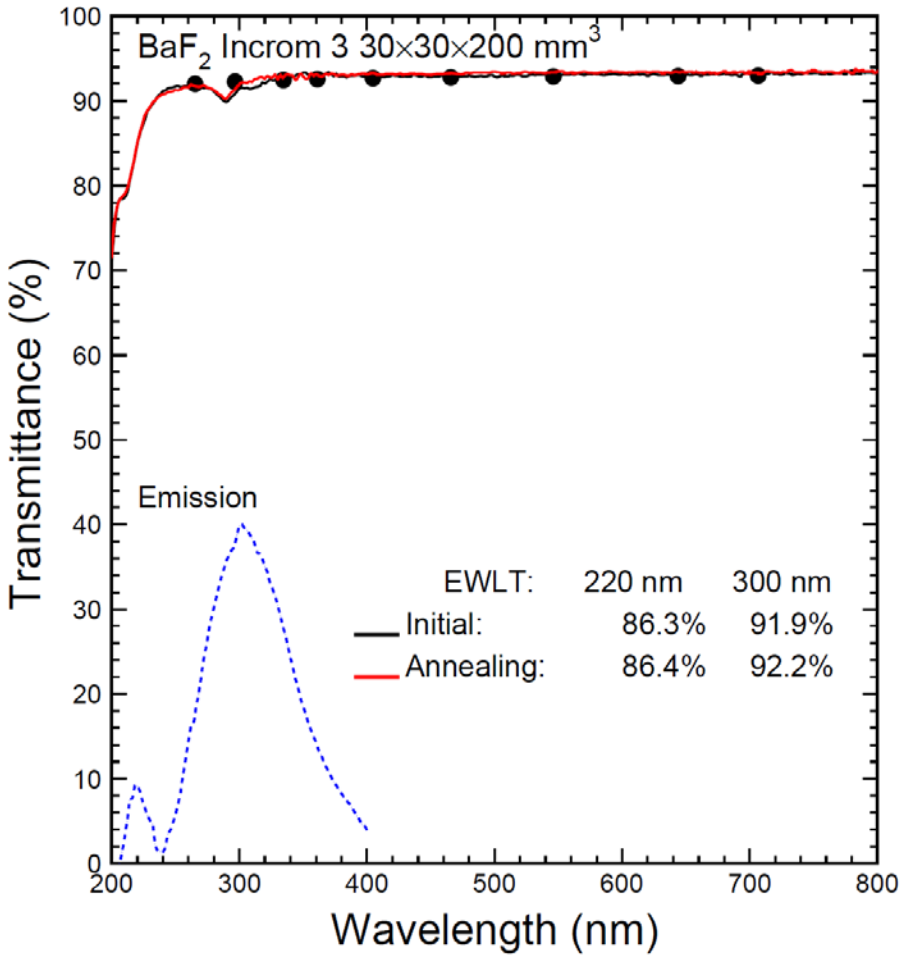




Thermal Annealing: Incrom 3

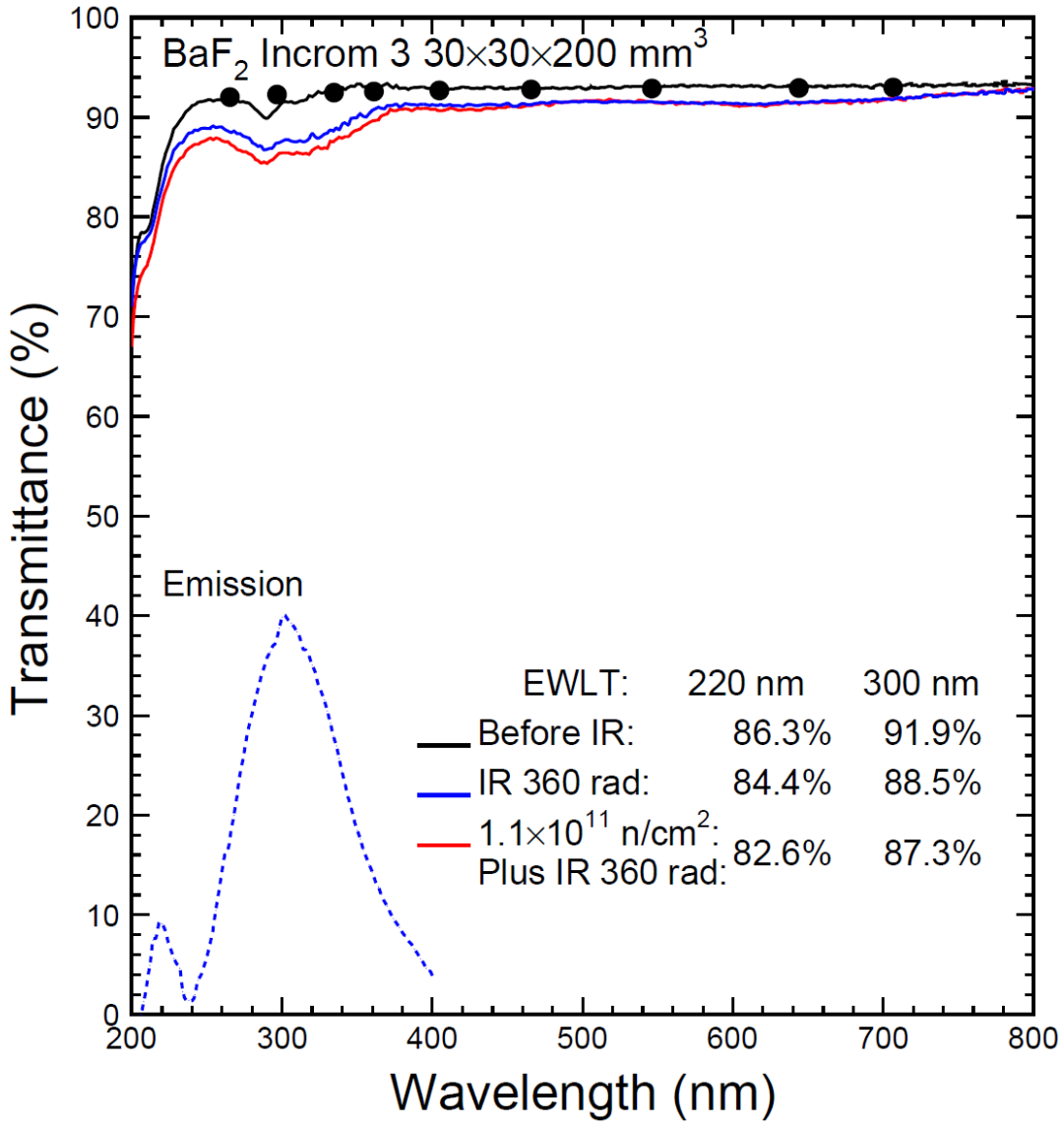
Thermal annealing is effective to remove neutron and ɣ-ray [1] induced damage





[1] NIMA 340 (1994) 442, http://www.hep.caltech.edu/~zhu/papers/94_nim_baf2.pdf

LT Loss: Comparison with 360 rad

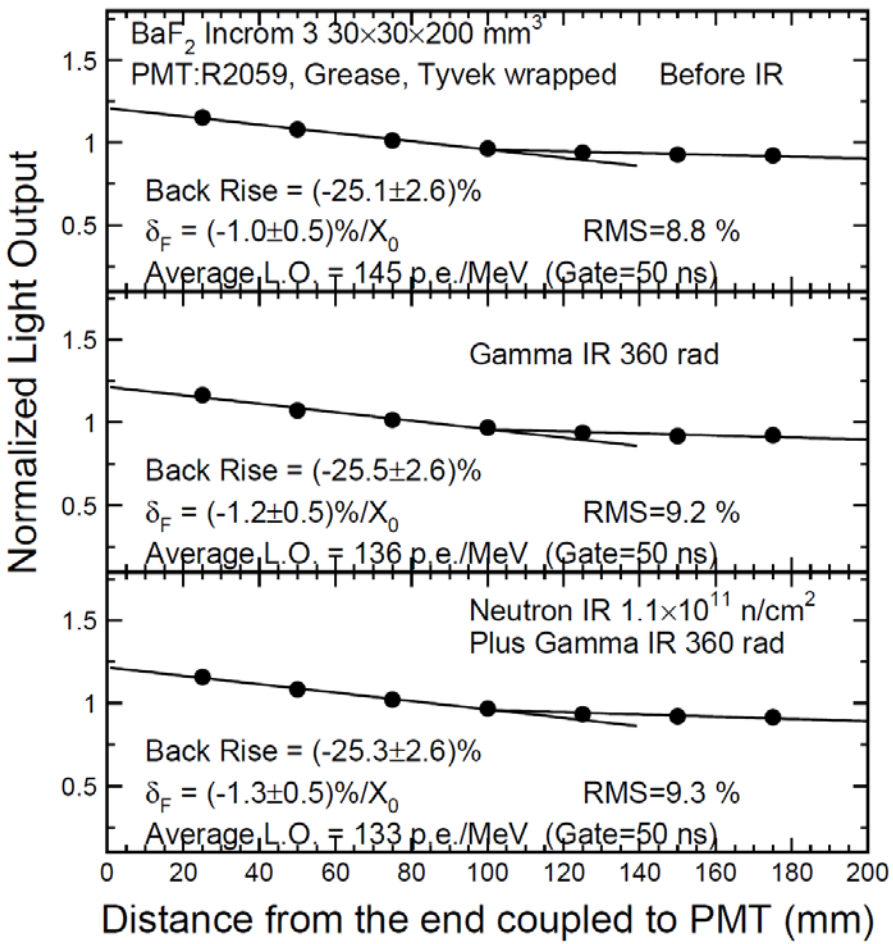


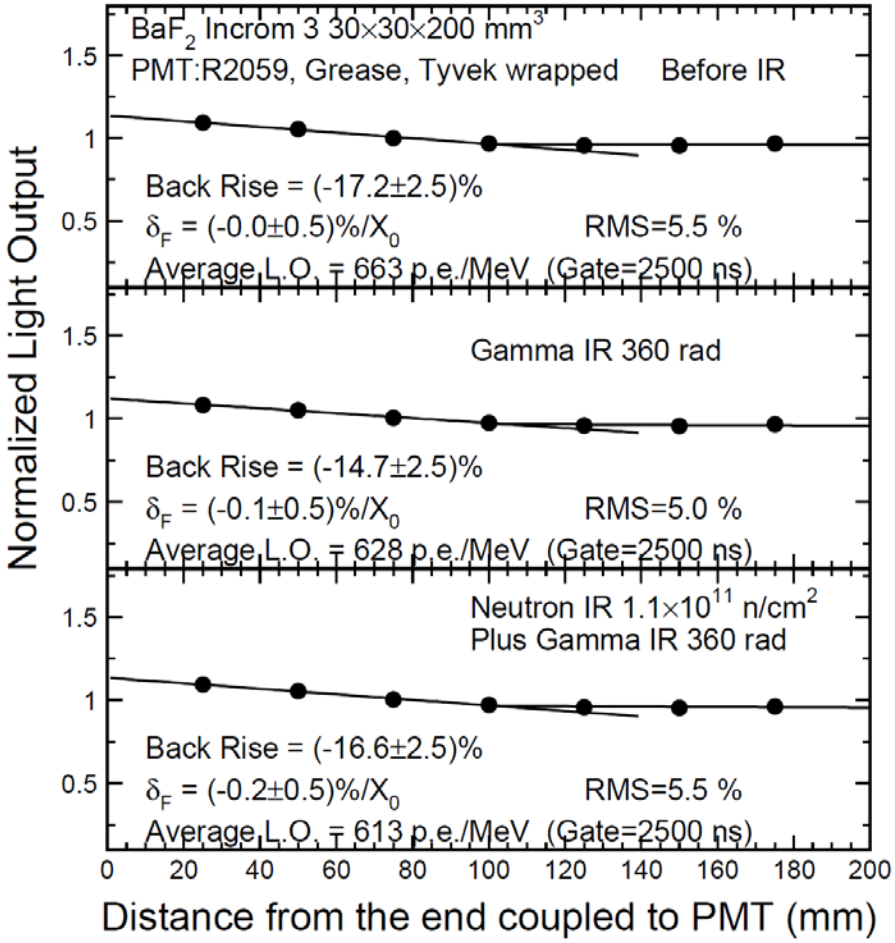
After a thermal annealing Incrom 3 went through a ɣ-ray irradiation of 360 rad. Its transmittance is compared to that after Cf-252 irradiation of 1.1×10^{11} n/cm^2.

The net damage caused by neutrons from Cf-252 sources is negligible.

LO Loss: Comparison with 360 rad

Neutron induced LO loss is negligible after ɣ-ray background subtraction

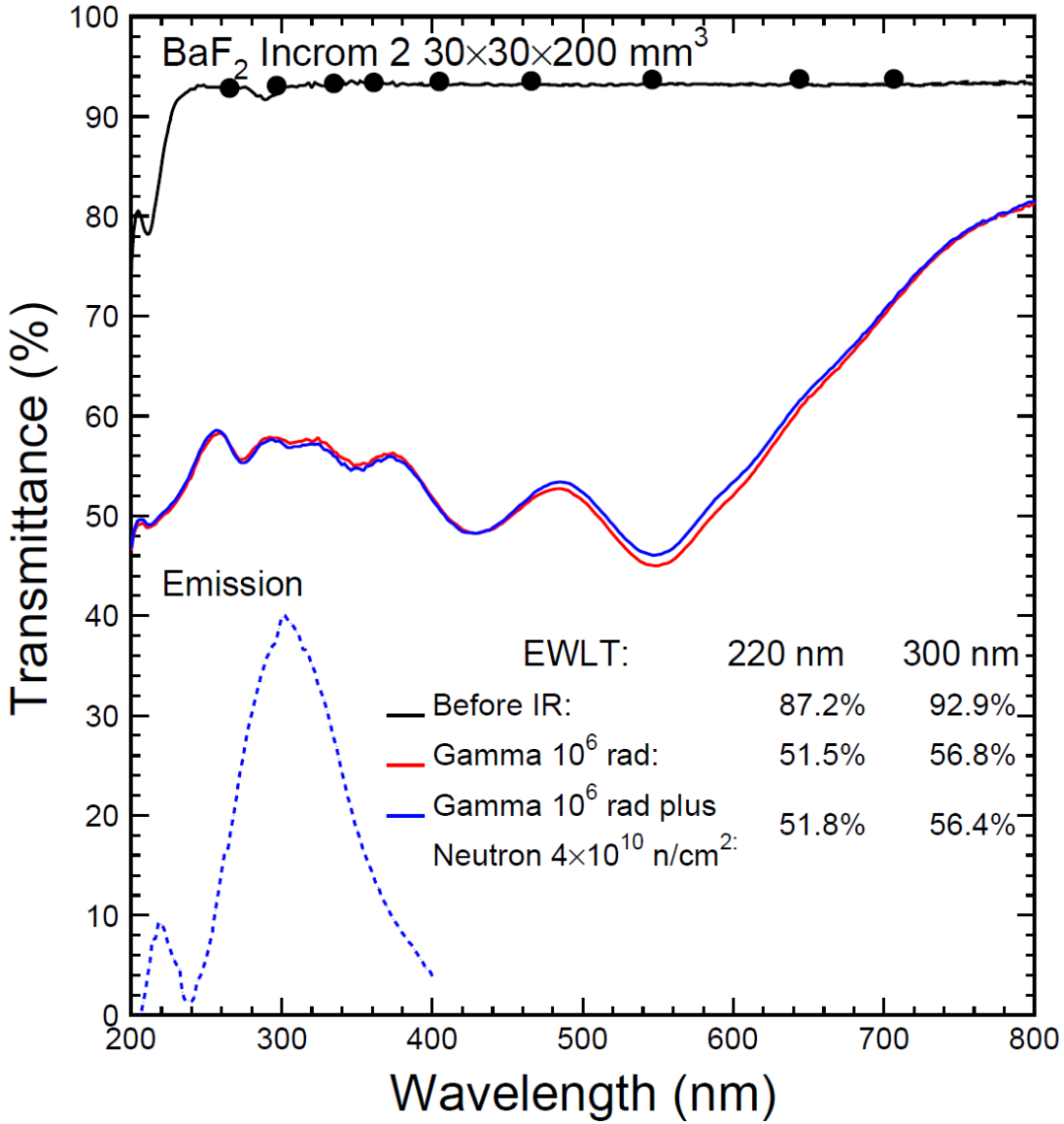




Incrom 2: 4 x 10^{10} n/cm^2 after 1 Mrad

Sample Incrom 2 went through additional neutron fluence of 4 x 10^{10} n/cm^2 after ɣ-ray irradiation of 1 Mrad.

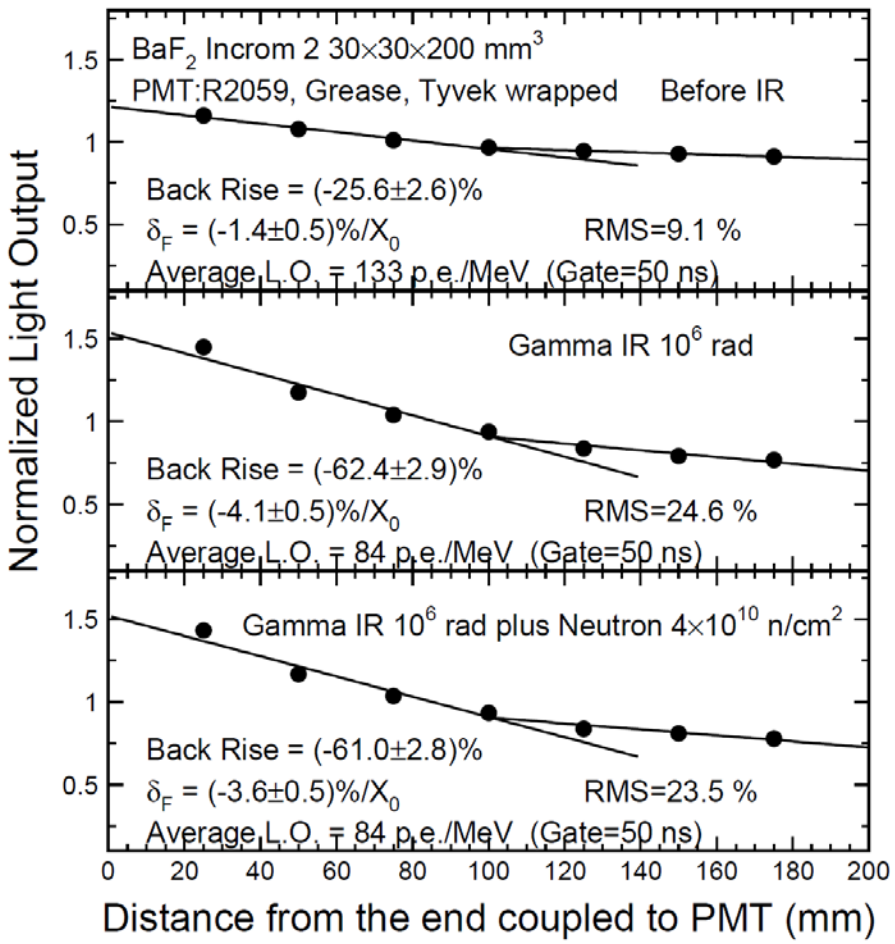
No additional damage was observed in LT, confirming that the damage caused by neutrons from Cf-252 sources in BaF_2 crystals is negligible.

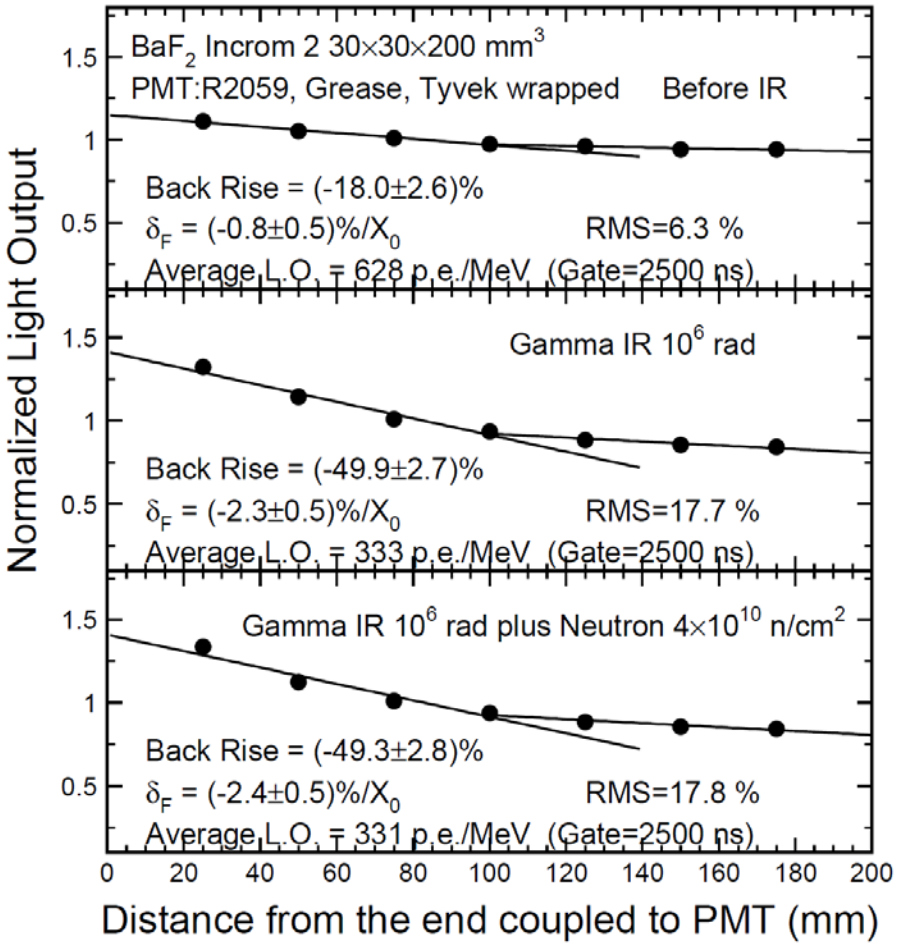


LO Loss: with Additional 4 x 10^{10} n/cm^2

50 ns: 133 to 84/84 p.e./MeV

2.5 μs: 628 to 333/331 p.e./MeV

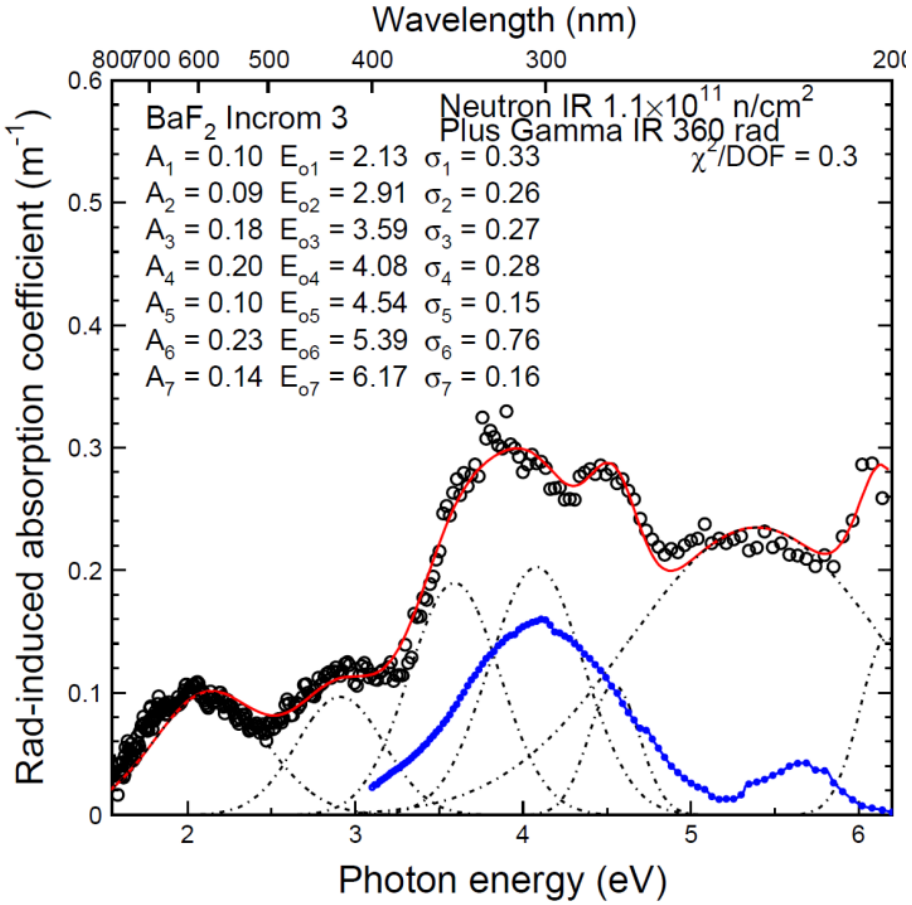


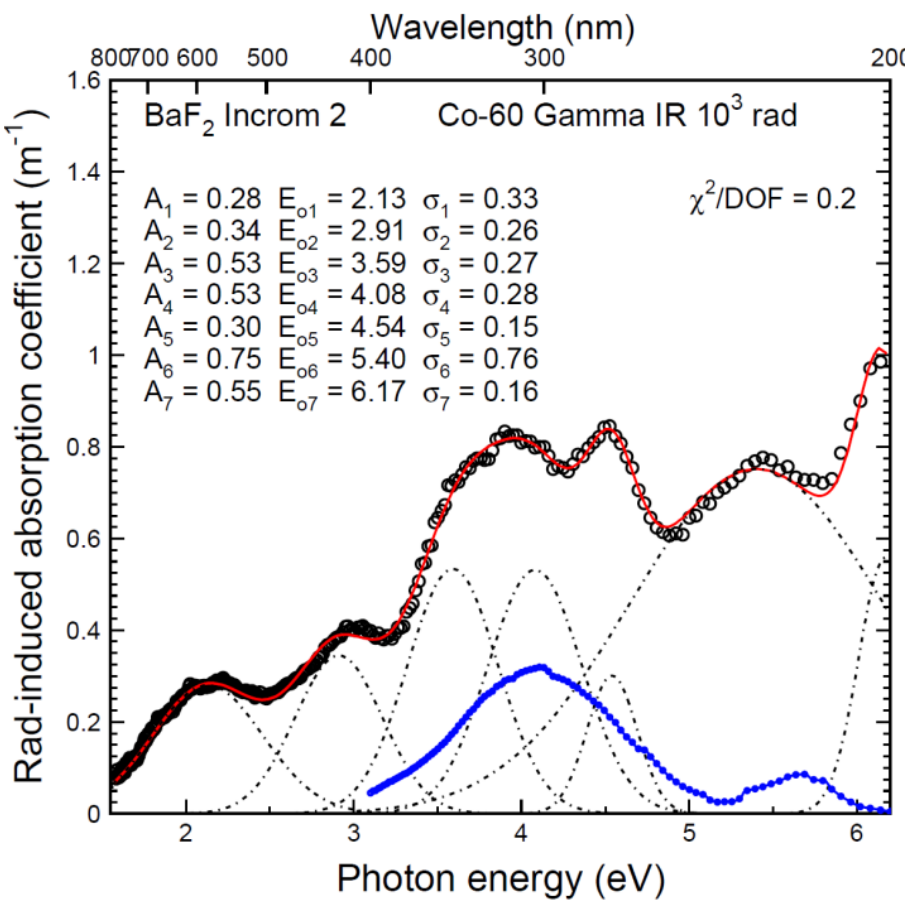


Additional neutrons of 4 x 10^{10} n/cm^2 cause no additional damage

BaF_2 Color Center Decomposition

Consistent color centers for ɣ-ray and neutrons, indicating similar nature





In seven color centers, two at 5.4 and 6.2 eV are relevant for the fast component

Summary

- High dose irradiation up to 120 Mrad at the JPL TID facility shows consistent damage in BaF_2 crystals from three vendors. BaF_2 crystals are radiation hard up to 120 Mrad.
- ɣ-ray background from Cf-252 sources was measured. After subtracting ɣ-ray background the net damage by neutrons in BaF_2 crystals is negligible.
- Adding 4×10^{10} n/cm^2 to another BaF_2 sample after 1 Mrad shows no additional damage, confirming the above conclusion.
- Combined with the INFN observation with 14 MeV neutrons, radiation damage caused by neutrons is not a concern for the Mu2e experiment.