Material characterization

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JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Experimental Physics II

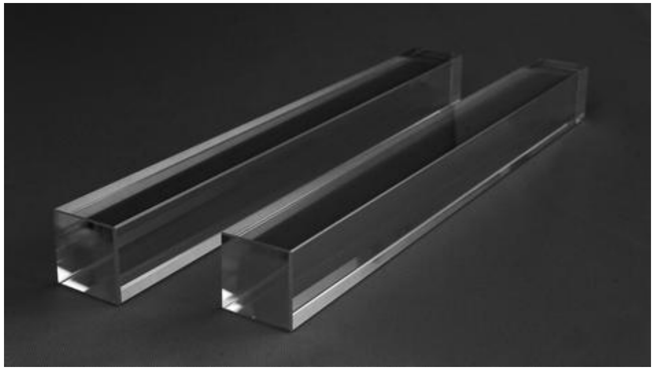
Bundesministerium für Bildung und Forschung

PWO properties

Parameter		CeF_3	LSO/LYSO:Ce	BGO	PWO	PWO-II
ρ	g/cm^3	6.16	7.4	7.13	8.28	
X_0	cm	1.77	1.14	1.12	0.89	
R_M	cm	2.6	2.3	2.3	2	
τ_{dec}	ns	30	40	300	6.5	
λ_{max}	nm	330	420	480	420	
n at λ_{max}		1.63	1.82	2.15	2.24/2.17	
L_R	% (L_R NaI)	5	75	9	0.3 (at 20 °C) 0.8 (at −25 °C)	0.6 (at 20 °C) 2.5 (at −25 °C)
hygroscopic		no	no	no	no	
dL_R/dT	%/°C	0.1	0	-1.6	-2.7 (at 20 °C)	-3.0 (at 20 °C)
dE/dx (MIP)	MeV/cm	6.2	9.6	9.0	10.2	

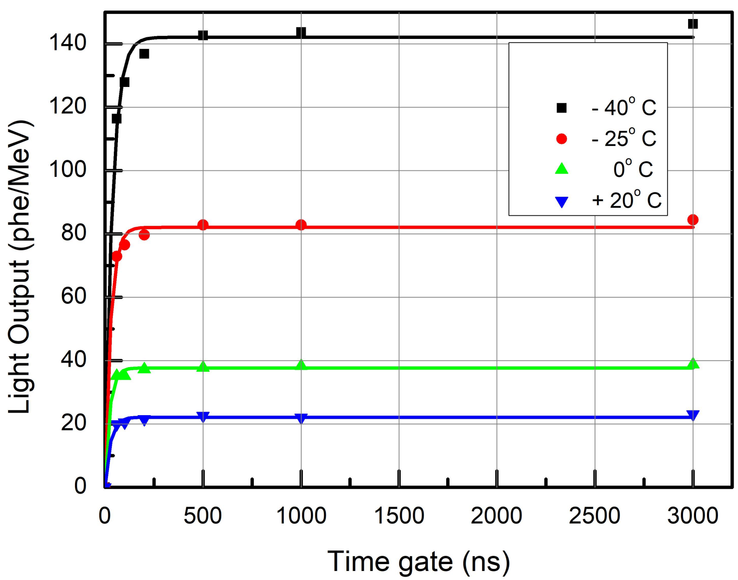
PWO is implemented or considered for electromagnetic calorimeters:

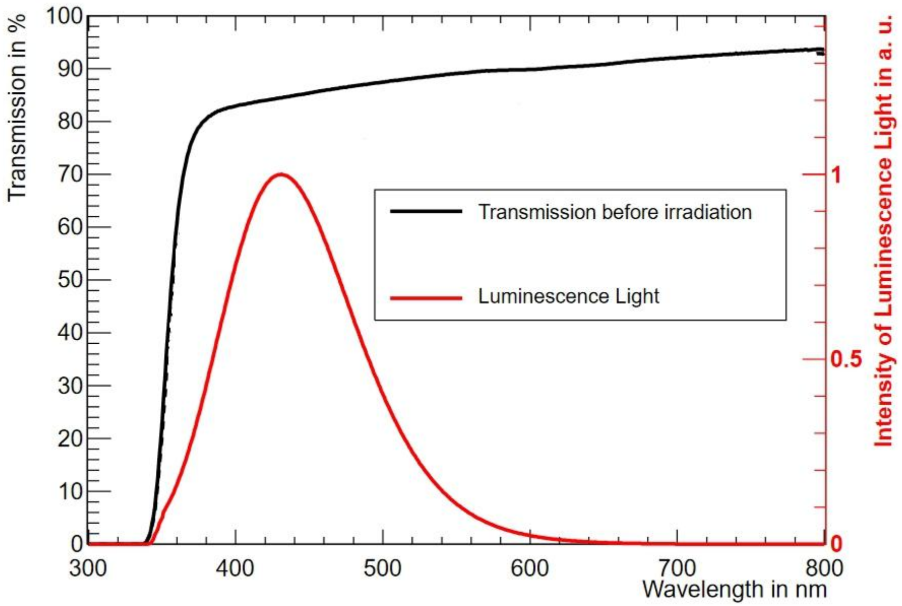
- the LHC experimetns CMS-ECAL and ALICE-PHOS (>100 000 PWO);
- PANDA-EMC detector at FAIR, GSI (~16 000 PWO-II)
- FCAL of GlueX detector and ECAL NPS at Jefferson Lab (~2500 PWO-II)



PWO properties

- Fast scintillation kinetics of PWO-II with a decay constant of about 10 ns
- The light yield of the lead tungstate crystal varies with temperature coefficient (–3 % / °C) in the temperature range from + 50 to – 50 °C.





PWO-II scintillator (20 × 20 × 200 mm^3) coupled to a Hamamatsu R2059 photomultiplier

total length: 200mm, tapered, all surfaces optically polished

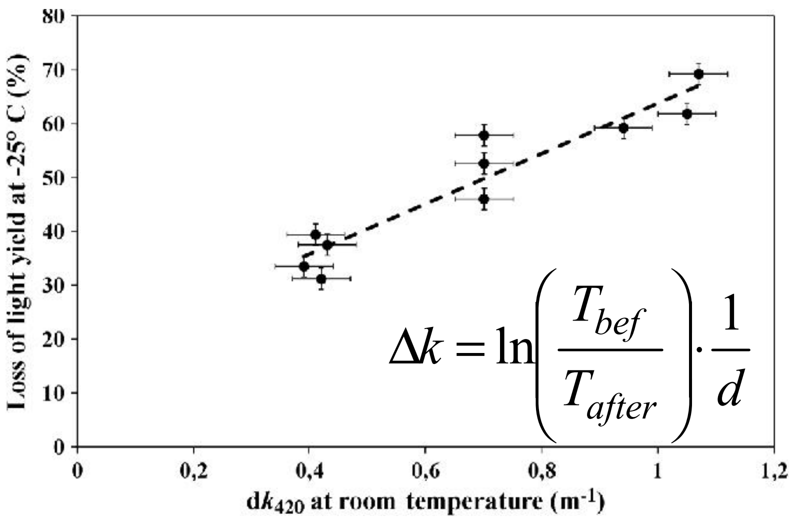
Radiation damage of PWO by e/m component

Radiation damage of PWO:

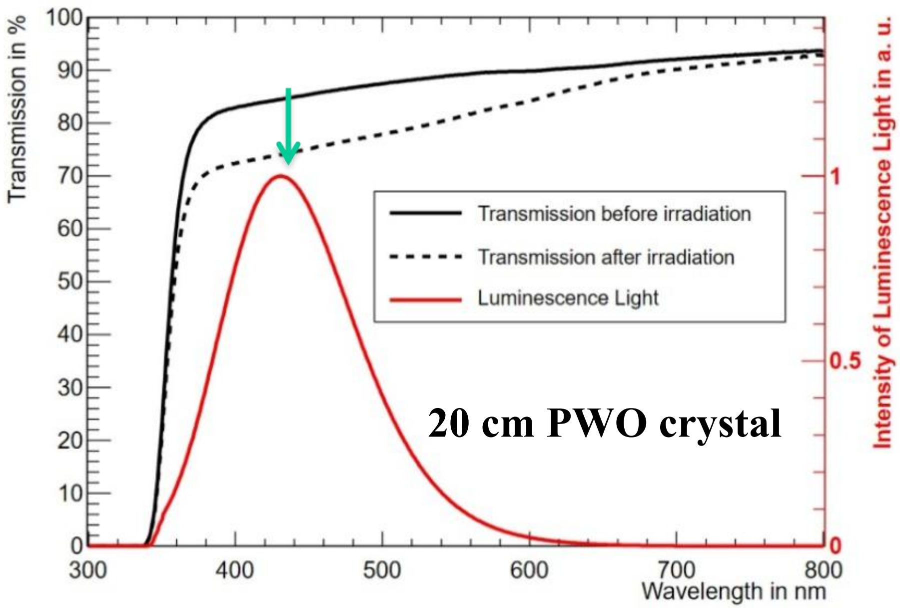
- creation of hot electrons and holes;
- free carrier separation during the thermalization and diffusion process;
- localisation of electrons and holes near lattice defects;

$$S = Y(T)\cdot \int N(E,z)\cdot C(z,\lambda)\cdot P(T,z,\lambda)\cdot M(T,\lambda)d\lambda dz$$

S- detector signal; Y – scintillation yield; N – normalized energy deposited profile along the Oz axis; C – transmission spectra; P – emission spectra; M –quantum efficiency of photo detector;



$$\Delta k = \ln\left(\frac{T_{bef}}{T_{after}}\right)\cdot\frac{1}{d}$$



The irradiation leads to the population of color centers (induced absorbtion) => Degradation of the transmission

=>Reduction of the light yield

=>Deterioration of the energy resolution

Recovery of radiation damage of PWO

Damage-recovery process is a thermo dynamical process in an open system, which can be further accelerated by injection of energy in appropriate form:

- Heating the crystal to increase spontaneous recovery;
- Energy can be delivered to a crystal via photons of selected wavelength – **stimulated recovery.**

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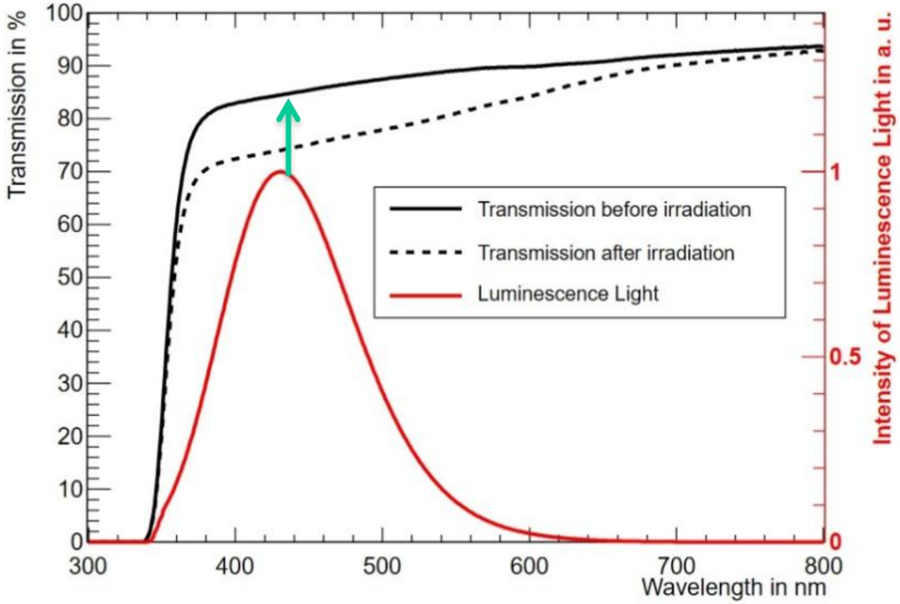

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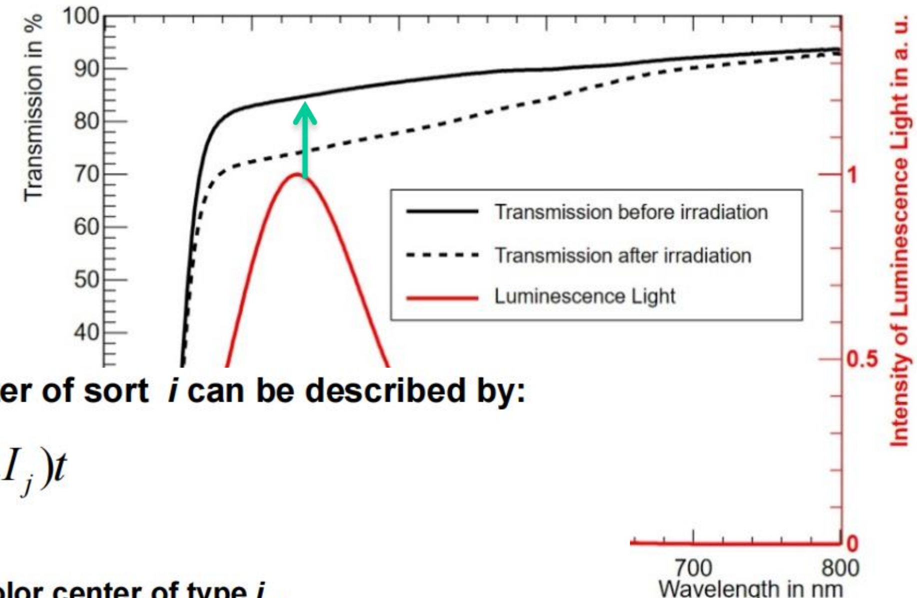


the relaxation process of the color center of sort *i* can be described by:

$$n_i = n_0 \exp(-w_T^i - \sum_j b_j I_j)t$$

where

***n_0*, *ni* - initial and current concentrations of the color center of type *i* ,**

$$w_T^i = A_i \exp(-E_{TA}/kT)$$ **-spontaneous relaxation probability,**

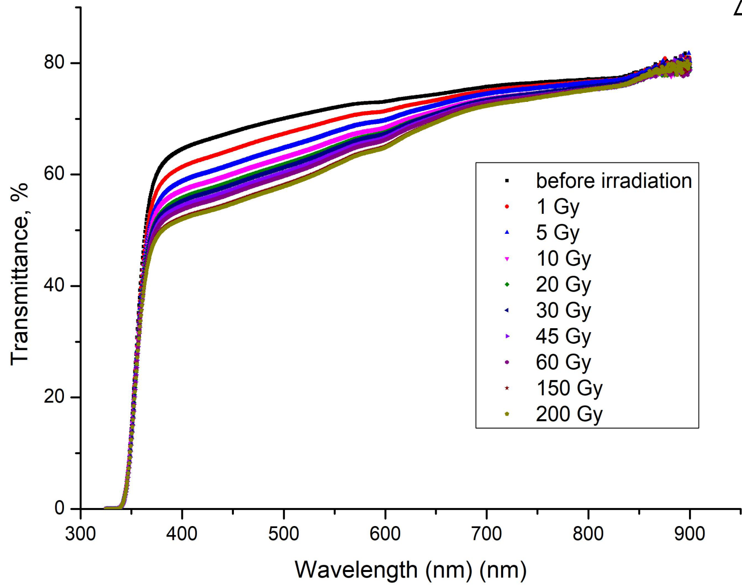
E_{TA} -thermo-activation energy of the color center, *k*-Boltzmann constant, *T* - temperature,

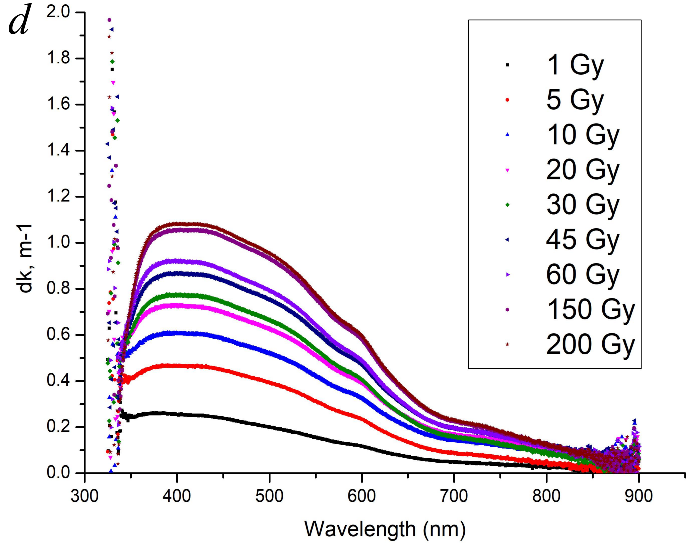
I_j -specific energy flux, **b_i describes the interaction of the color center with a flux of specific energy.**

Radiation damage of PWO by e/m component at RT

- 20 cm PWO crystal
- high intensity γ-source 60-Co with an activity of $6.8 \bullet 10^{12}$ Bq
- conventional double beam spectrometer - VARIAN
- 44 Gy/h, 21 Gy/h

$$\Delta k = \ln\left(\frac{T_{bef}}{T_{after}}\right)\cdot\frac{1}{d}$$





Radiation damage of PWO by e/m component at RT

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- high intensity γ-source 60-Co with an activity of $6.8 \bullet 10^{12}$ Bq
- conventional double beam spectrometer - VARIAN
- 44 Gy/h, 24 Gy/h

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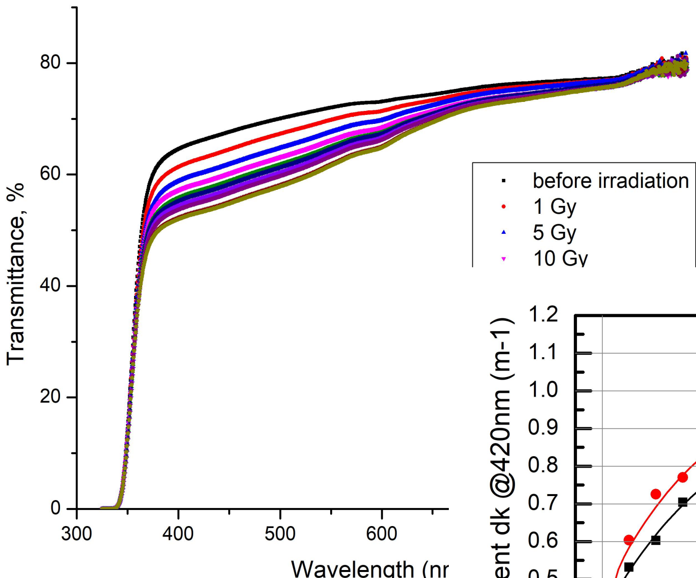
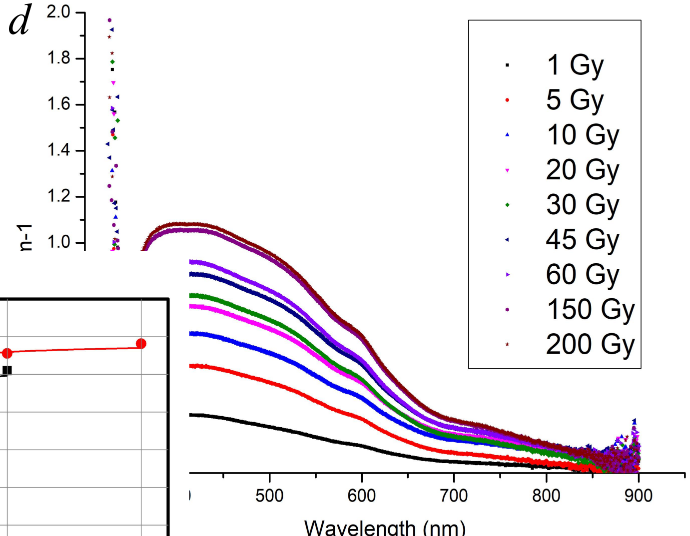
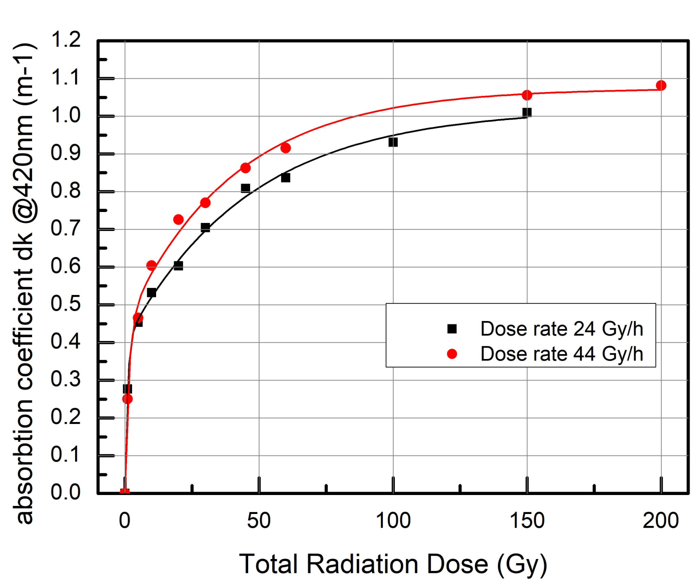
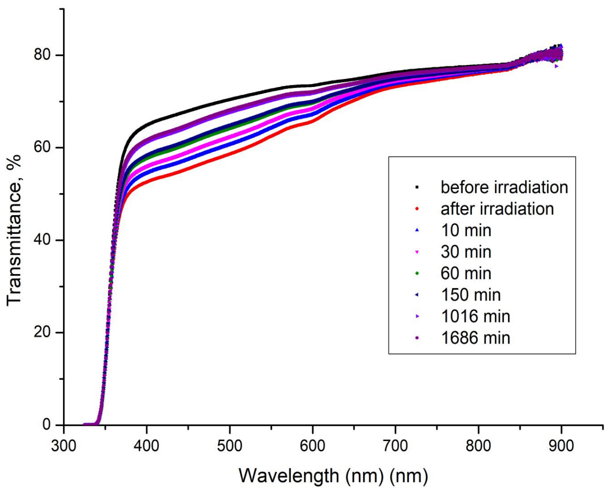






Recovery of radiation damage of PWO at RT after e/m

- 20 cm PWO crystal
- the stimulated recovery system includes few laser diodes with peak wavelengths at 850, 980, 1060 and 1310 nm, a laser diode controller and optical fibers bringing the light into the PWO crystal.
- conventional double beam spectrometer - VARIAN 4
- Recovery after 200 Gy (Dose rate = 44 Gy/h)



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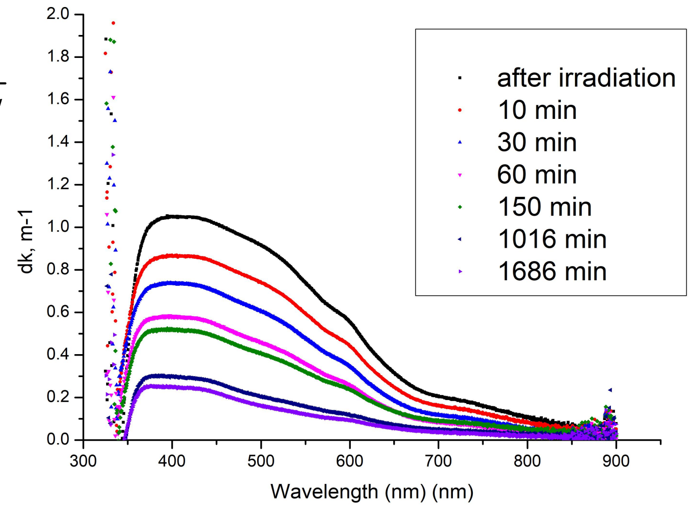

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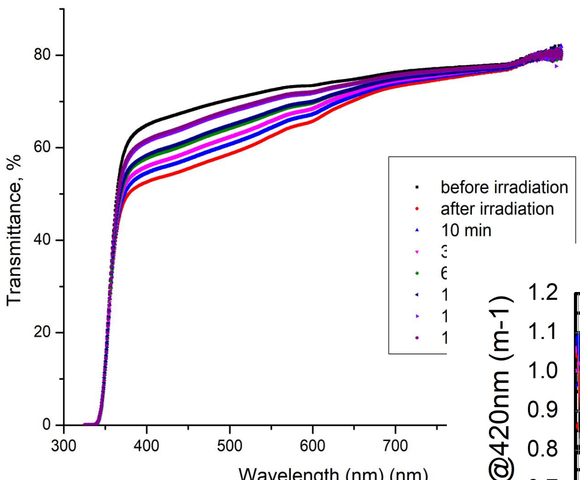

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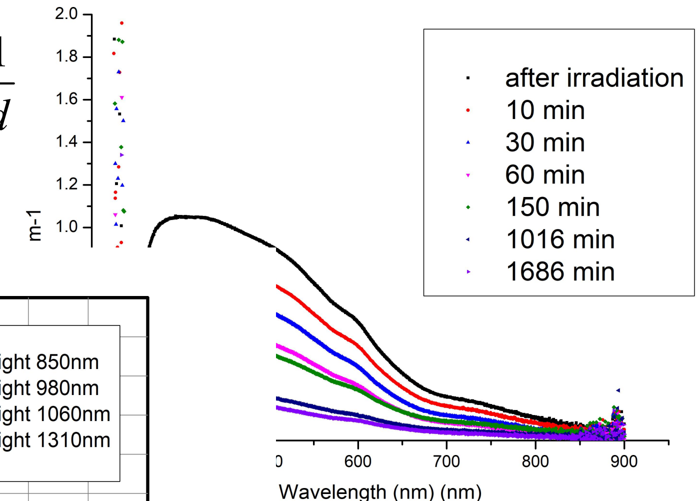
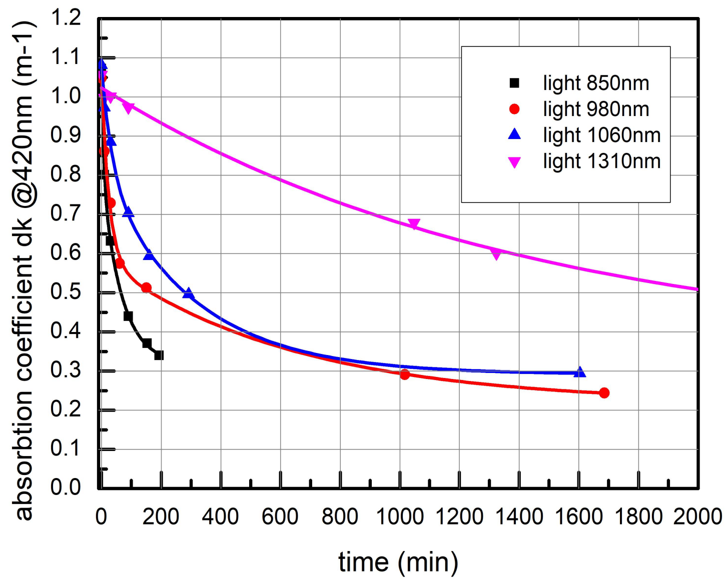
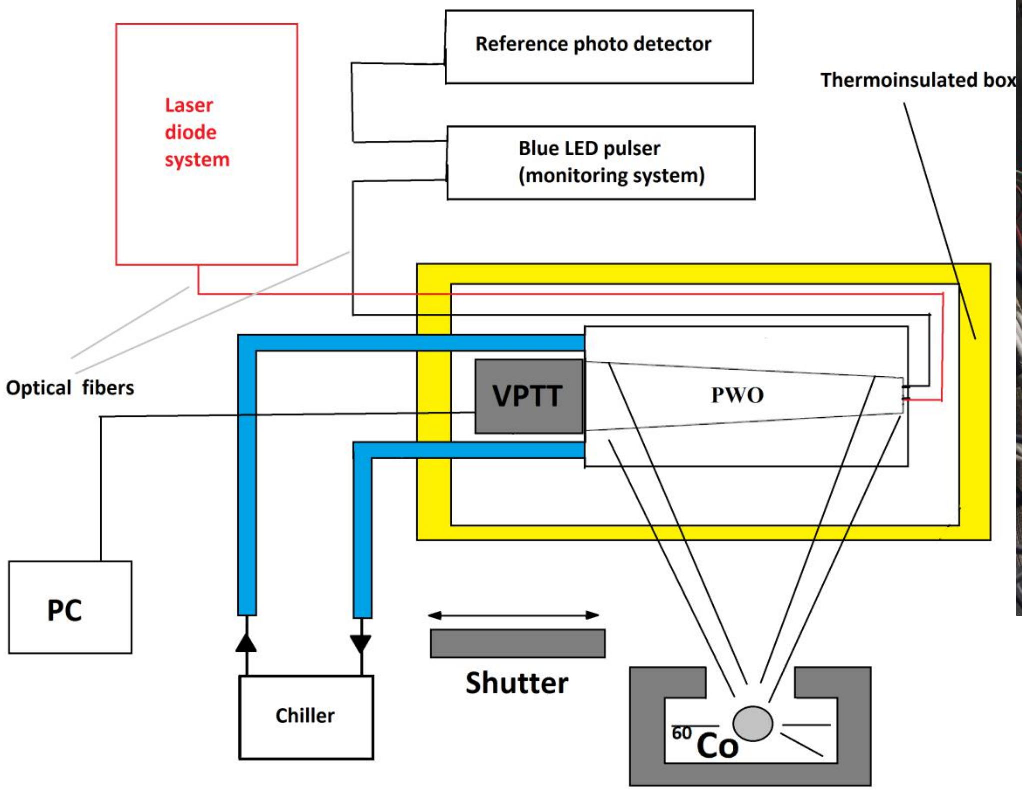
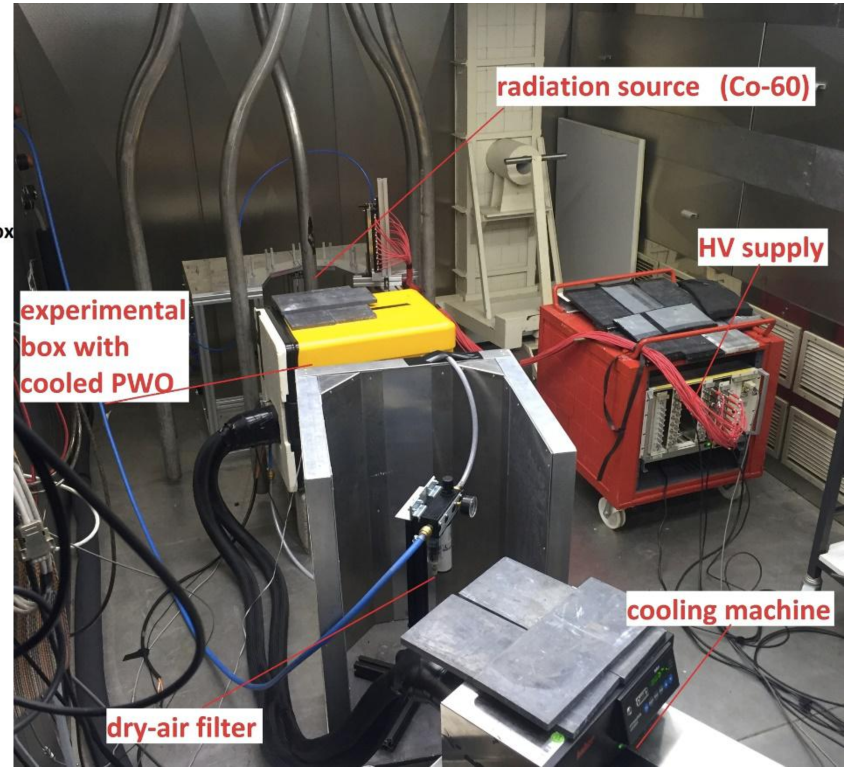




Experimental setup

Schematic layout of the experimental setup





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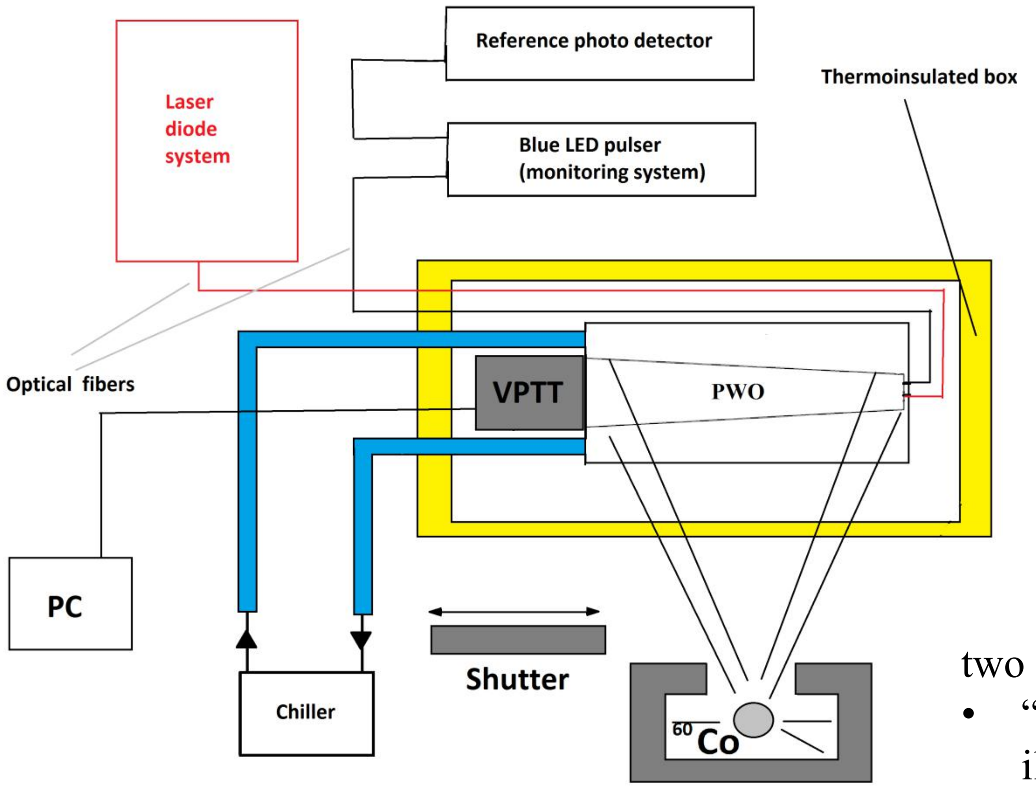
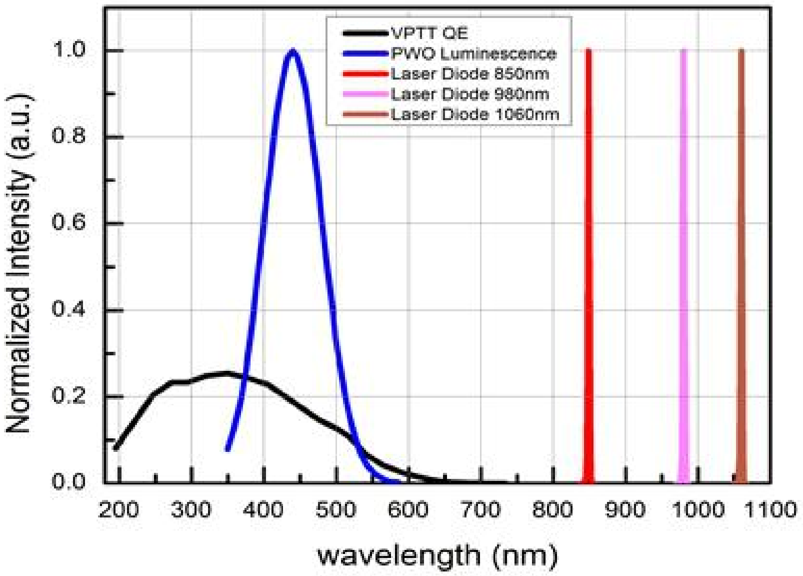


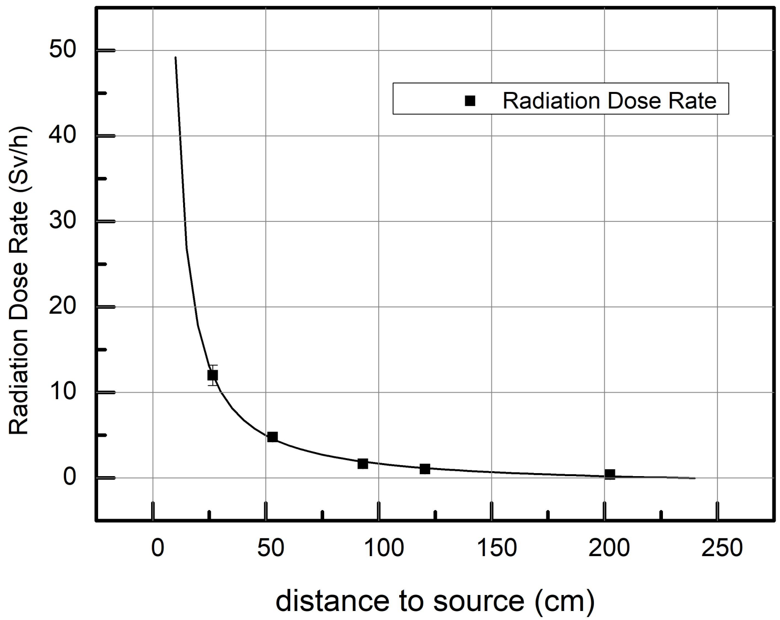


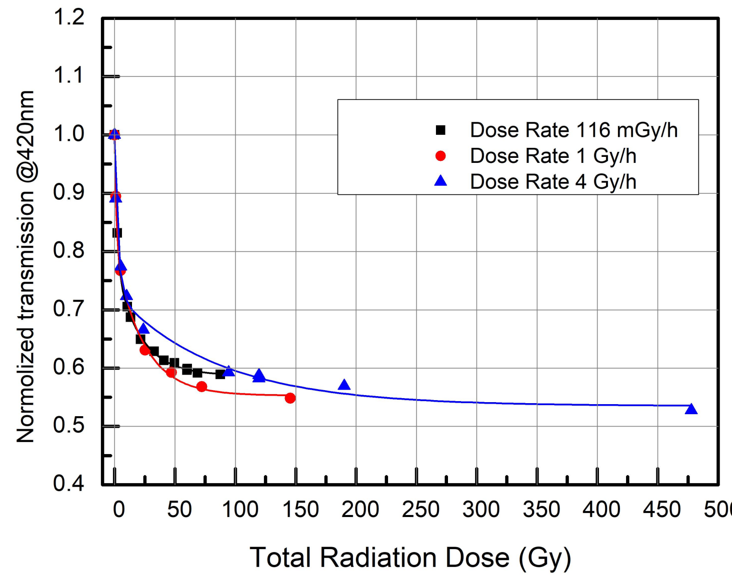
two modes of stimulated recovery system:

- "offline" mode - stimulated recovery via illumination of external light from laser diodes *after* irradiation (during beam-off periods)
- "online" mode –illumination *during* calorimeter operation.

Radiation damage of PWO by e/m component at -25^{o} C

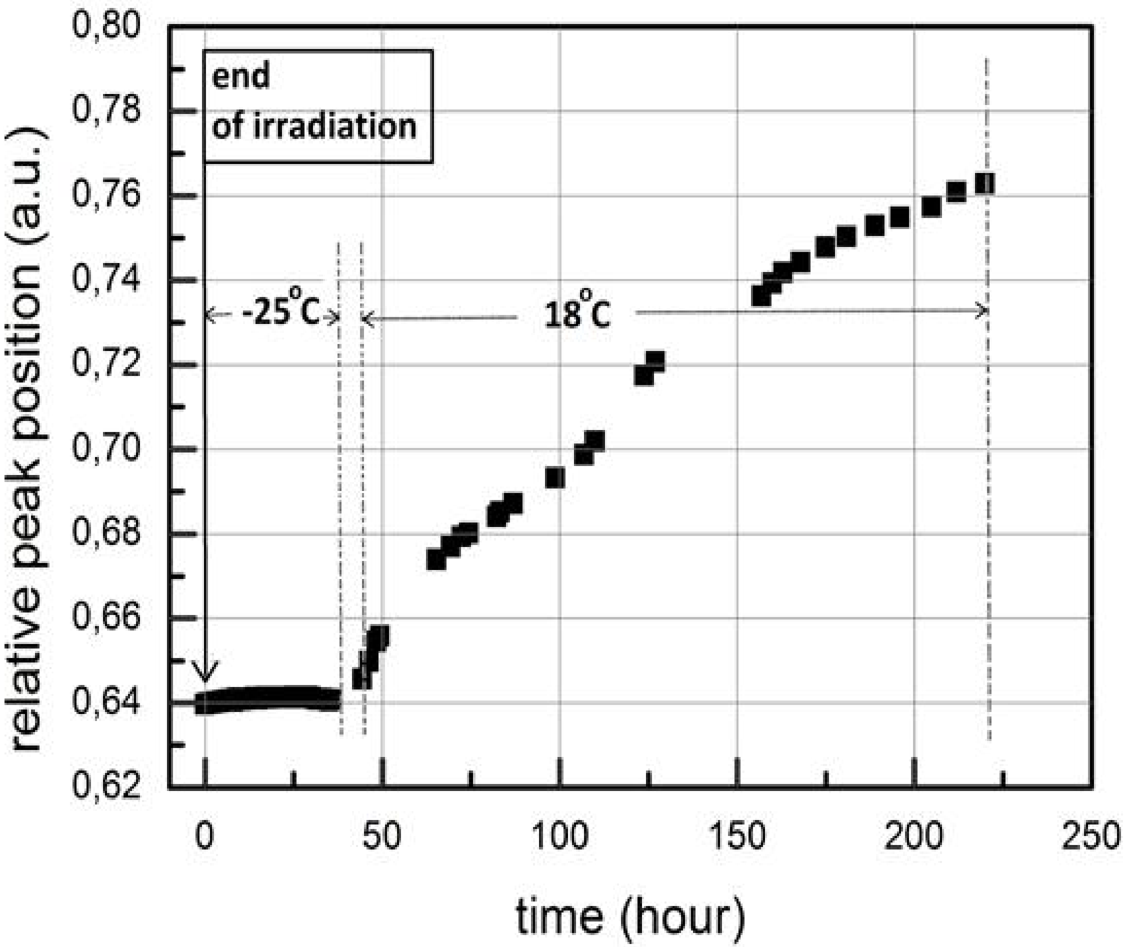
- 20 cm PWO crystal
- high intensity γ-source 60-Co with an activity of $6.8 \bullet 10^{12}$ Bq
- conventional double beam spectrometer - VARIAN
- 44 Gy/h, 21 Gy/h





Recovery (1)

Spontaneous recovery of the PWO crystal after the irradiation at -25° C and +18 ° C

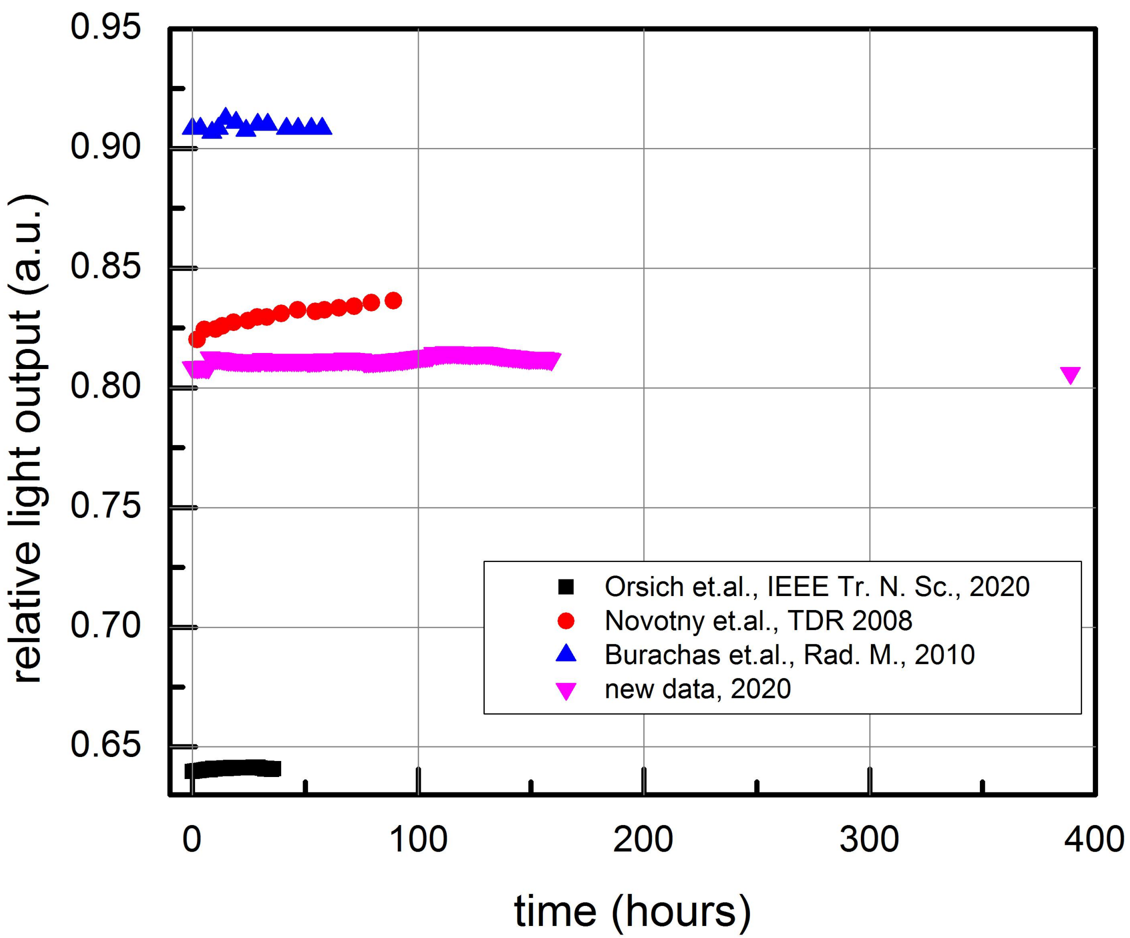


Dose rate for new data was 4.6 Gy/h during 6.5 h (integral dose = 30 Gy)

- significant spontaneous recovery at the RT in comparison with low temperature

Recovery (2)

Spontaneous recovery of the PWO crystal after the irradiation at -25° C



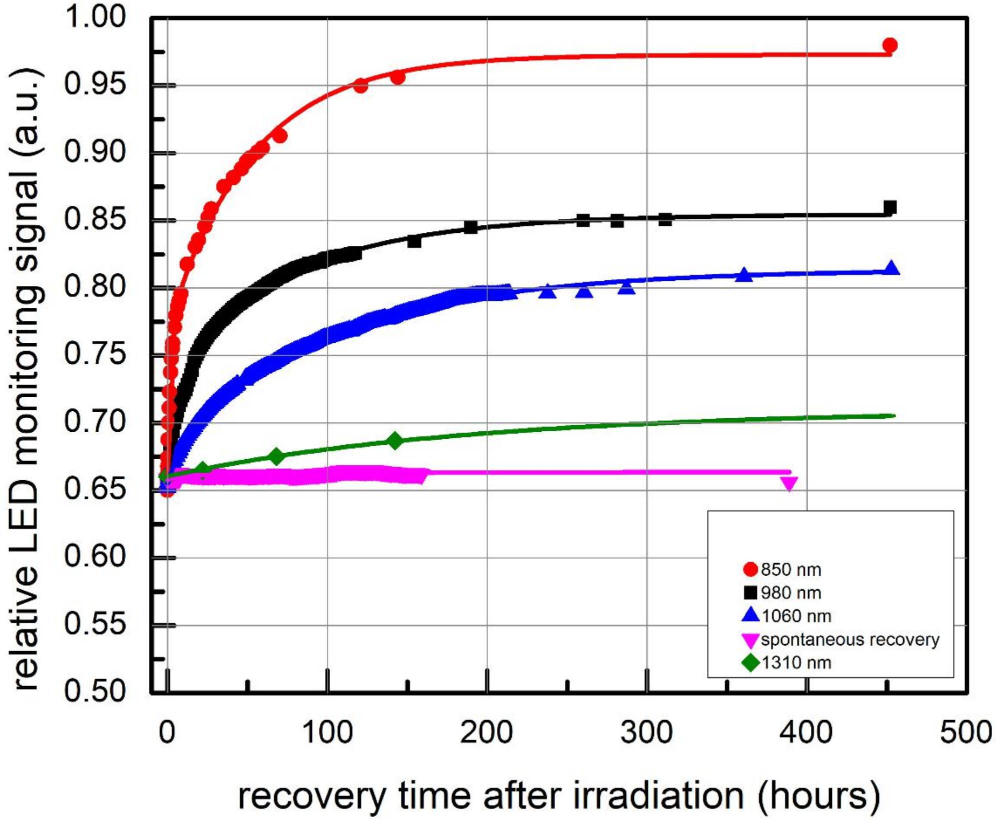
Dose rate for new data was 6.4 Gy/h during 4.5 h (integral dose = 30 Gy)

- comparison with previous study

- no significant spontaneous recovery at the low temperature during <u>**380**</u> hours of the measurement.

Recovery (3)

The spontaneous and stimulated recovery at -25° C of PWO crystal after gamma-irradiation.



Dose rate of 6.4 Gy/h during 4.5 h (integral dose of 30 Gy)
Light intensity I = $1 \bullet 10^{17}$ ph/s

- Fitting function:

850, 980, 1060nm:

$$1 - a_1 e^{-\frac{t}{\tau_1}} - a_2 e^{-\frac{t}{\tau_2}} - c \, ,$$

1310 nm:

$$1 - a \; e^{-\frac{t}{\tau}} - c$$

where $a = a_1 + a_2$-sum of recovery;
τ_1 – fast recovery constant;
τ_2 – slow recovery constant
c – residual damage

Experimental results (4)

Fit parameters of recovery

Fitting functions: $1 - a_1 e^{-\frac{t}{\tau_1}} - a_2 e^{-\frac{t}{\tau_2}} - c;\ 1 - a\ e^{-\frac{t}{\tau}} - c$

$R_i = \frac{a_i \tau_i}{\sum_{i=1}^{2} a_i \tau_i}$, where $a = a_1 + a_2$

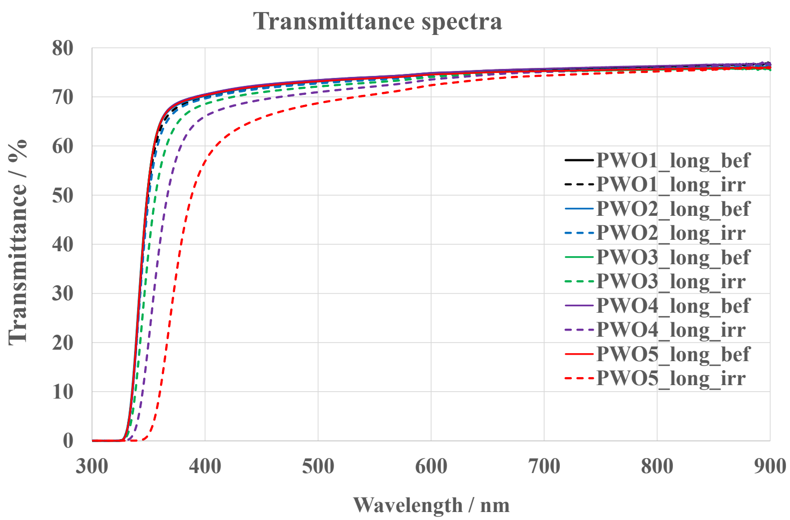
Illumination wavelength	'a', sum recovery (%)	'τ_1', fast recovery constant (hours)	'R_1', contribution fast constant(%)	'τ_2', slow recovery constant (hours)	'R_2', contribution slow constant (%)	'c', residual damage (%)
464 nm	33.0	0.047	4.5	1.34	95.5	2
850 nm	32.0	1.9	2.0	52.6	98.0	3
980 nm	19.6	10.7	8.6	81.5	91.4	14
1060 nm	15.2	10.4	2.3	106.3	97.7	19
1310 nm	4			185.9	100	29

Illumination by photons with a wavelength of 850 nm leads to the appearance of flashes (noise on low channels) after several tens of hours.

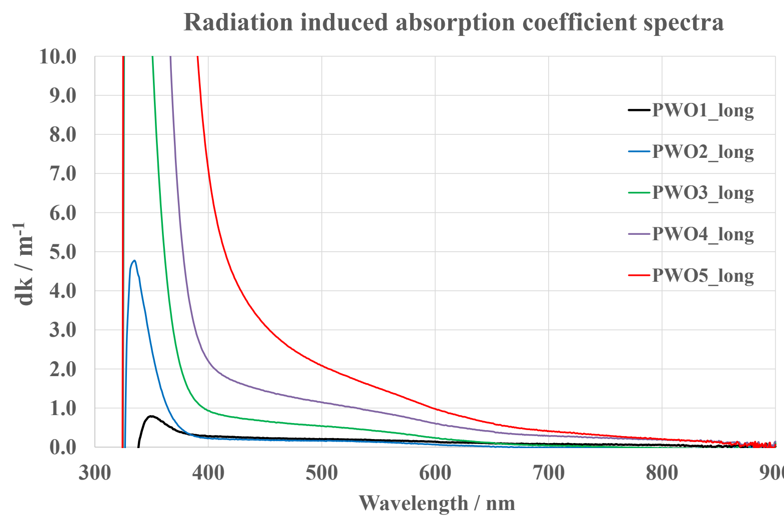
- **Limit of implementing the «online» recovery mode placed at wavelength longer then 850 nm!!**

Radiation damage of PWO by hadron component at RT

- 3 cm PWO crystal
- Irradiation were done at CART-KVI (Groningen, Netherlands) with 190 MeV proton beam
- conventional double beam spectrometer - VARIAN 4
- Fluences: Sample 1: 6×10^{11} p/cm^2 ; Sample 2: 1.5×10^{12} p/cm^2 ; Sample 3: 6×10^{12} p/cm^2 ; Sample 4: 1.5×10^{13} p/cm^2 ; Sample 5: 6×10^{13} p/cm^2
- Measurments were done in ~1 year after irradiation.



$$\Delta k = \ln\left(\frac{T_{bef}}{T_{after}}\right) \cdot \frac{1}{d}$$



- **creation of macro defects**
- **highly ionizing fission products**
- **ion displacements**

A band-edge shift (*) is observed with proton-damage , unlike for γ -damage
(*) explanation likely to be disorder causing an Urbach-tail

Conclusion

- The stimulated recovery process is an effective application to reduce radiation damage of the EMC units.

- Since VPTT has a negligible quantum efficiency in the infrared region, the stimulated recovery with light between **850 nm and 1100 nm** opens an opportunity for the “online” recovery mode at low temperature at low dose rate (5-30 mGy/h).
- Stimulated recovery can substantially improve the detector performance and prolong its lifetime under tolerable conditions at low temperature.

- The damage mechanisms of lead tungstate crystal under the irradiation with relativistic and 150 MeV protons appear to be identical.
- Full recovery of the hadron damage is
- reachable only after annealing at temperatures above 200 C.

Conclusion

- The stimulated recovery process is an effective application to reduce radiation damage of the EMC units.

- Since VPTT has a negligible quantum efficiency in the infrared region, the stimulated recovery with light between **850 nm and 1100 nm** opens an opportunity for the “online” recovery mode at low temperature at low dose rate (5-30 mGy/h).

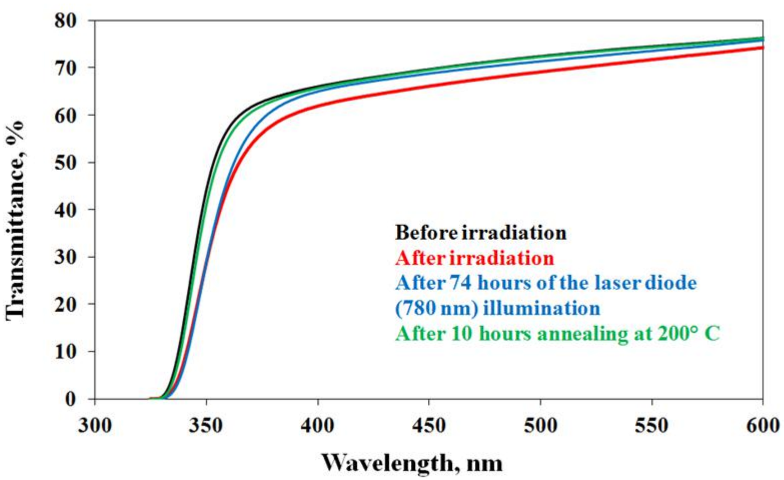
- Stimulated recovery can substantially improve the detector performance and prolong its lifetime under tolerable conditions at low temperature.

Thank you for your attention!

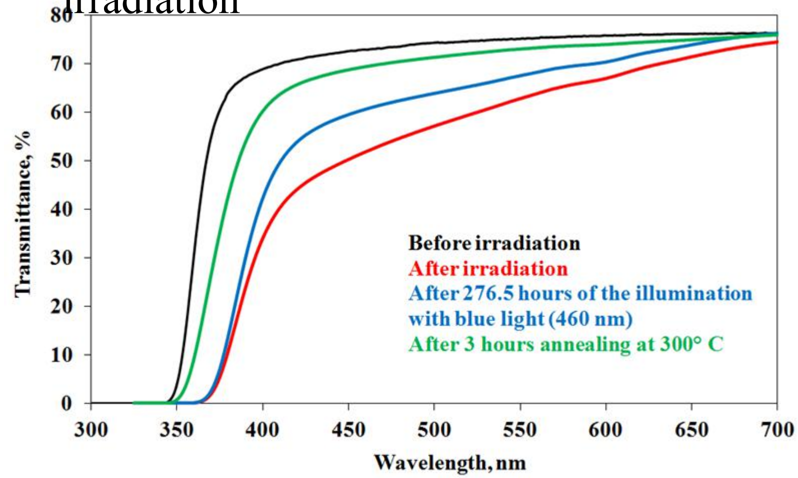
Backup slides

Recovery of radiation damage of PWO at RT after handrons

- 5 cm PWO crystals
- recovery system includes laser diode with peak wavelengths at 780 nm and optical fibers bringing the light into the PWO crystal.
- conventional double beam spectrometer - VARIAN 4
- $PbWO_4$ irradiated by 150 MeV protons *@CART-KVI, Groningen, Netherlands*
- Fluence = 1.8×10^{13} protons/cm^2
- Measurement were done in 4 mounth after irradiation

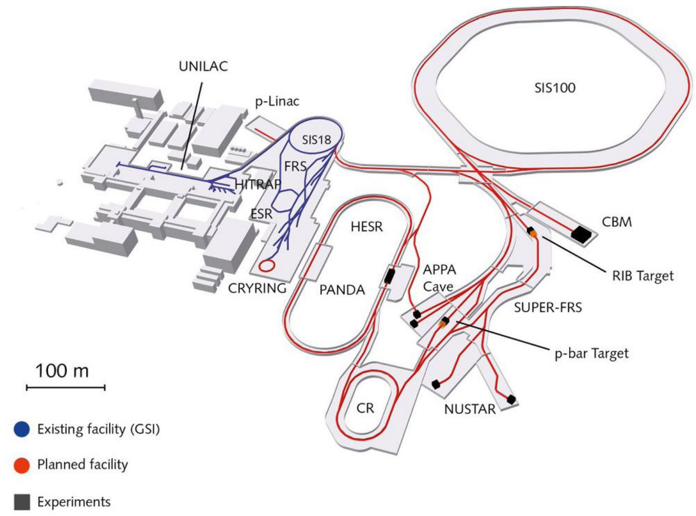


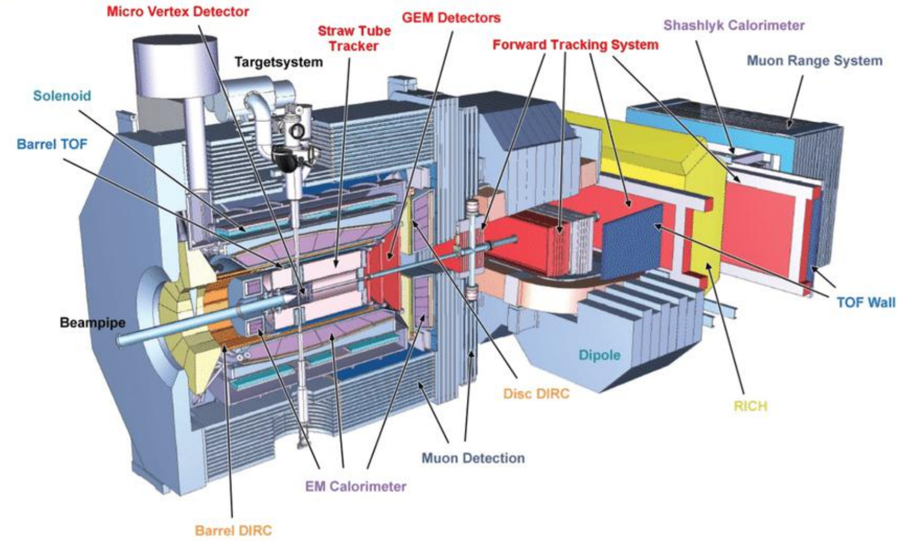
- 22 cm PWO crystals
- recovery system includes laser diode with peak wavelengths at 460 nm (Light intensity $I = 5.8 \cdot 10^{16}$ ph/s) and optical fibers bringing the light into the PWO crystal.
- conventional double beam spectrometer - VARIAN 4
- $PbWO_4$ irradiated by 24 GeV protons
- *@CERN, Switzerland*
- Fluence = $3 * 10^{13}$ protons/cm^2
- Measurement were done in 3 mounth after irradiation



Longer annealing at 350°C allows to reach a full recovery
G. Dissertori et al. NIM A 684 (2012) pp.57-62

$\overline{\text{P}}$ANDA at FAIR

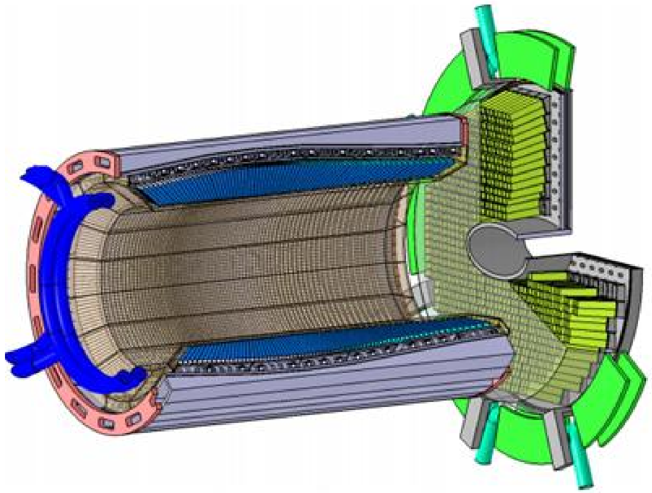




- Accelerator facility at Darmstadt (GSI) under construction
- Primary beams: p up to 30 GeV/c, heavy ion beams up to 35 GeV/c (U^{92+})
- Secondary beams: Radioactive beams, $\overline{p}$
- $\overline{\text{P}}$ANDA is located at High Energy Storage Ring (HESR) with stochastic and electron cooling of $\overline{p}$ beams between 1.5 GeV/c and 15 GeV/c
- High Luminosity $2 \bullet 10^{32}\ cm^{-2}s^{-1}$
- High resolution $4 \bullet 10^{-5}$
- Fixed target experiment (hydrogen or nuclear)

- Target spectrometer and forward spectrometer
- $\overline{\text{P}}$ANDA physics program will cover:
  - Charmonium spectroscopy
  - Gluonic excitations
  - In-medium effects of hadronic particles
  - Open-charm spectroscopy
  - Hypernuclei
  - Electromagnetic processes

$\overline{\text{P}}$ANDA EMC



- Barrel part plus two endcaps (16000 lead tungstate crystals + LAPD/VPTT)

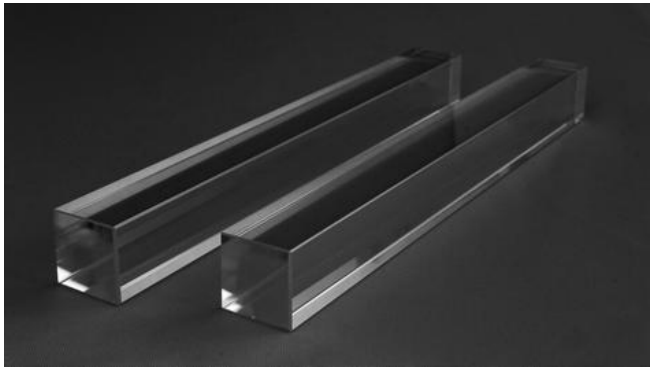
Requirements:

- Full reconstruction of multi-photon and lepton-pair channels
- Low energy threshold (10 MeV)
- Good energy $\sigma_E/E \leq 1\%$ $\frac{\leq 2\%}{\sqrt{E/GeV}}$ and spatial resolution for photons up to 15 GeV
- Full angular coverage (98.8 % of 4π), high yield and background rejection
- Working temperature -25^0 C
- Radiation hardness (radiation dose rate up to 125 Gy/a at full luminosity)

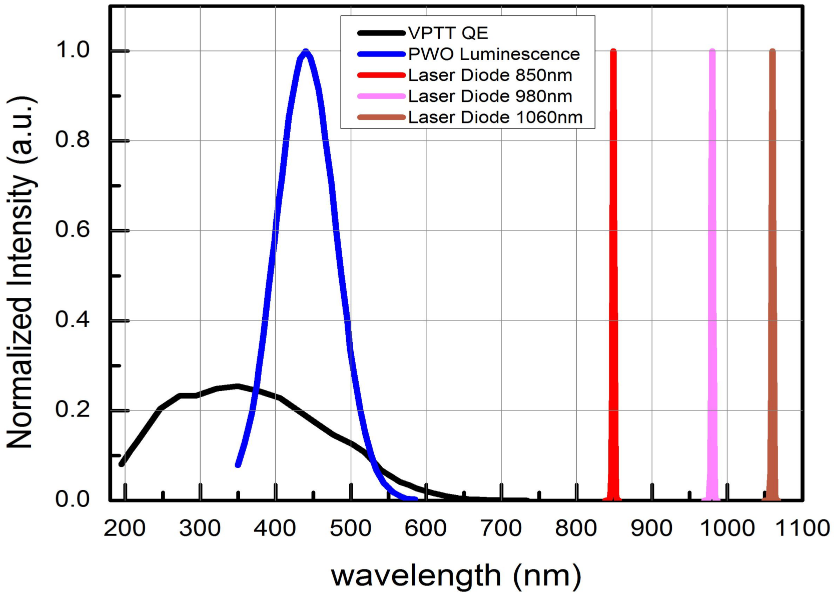
$PbWO_4$ (PWO-II):

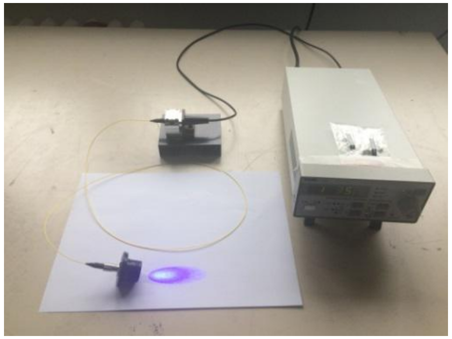
- density 8.28 g/cm^3
- radiation length X_0= 0.89 cm
- Moliere radius R_M =2.19 cm
- Short decay time 6.5 ns
- Light yield ~100 ph/MeV at RT

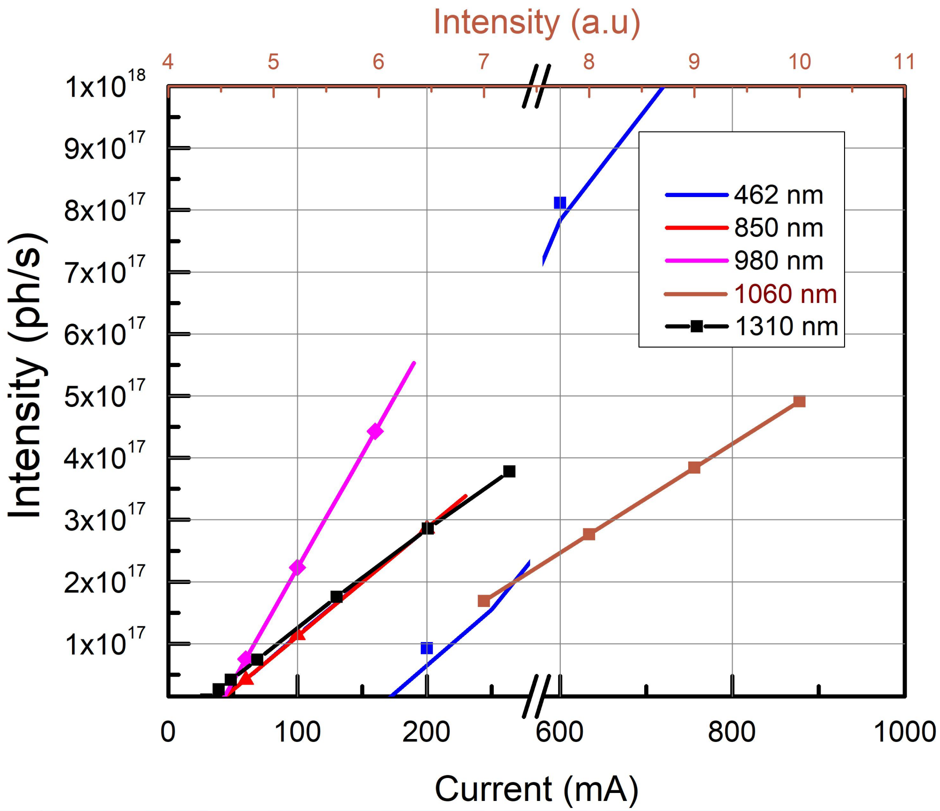
(4 times more at -25^0 C due to temperature gradient −3 % per K)



- Laser diode system

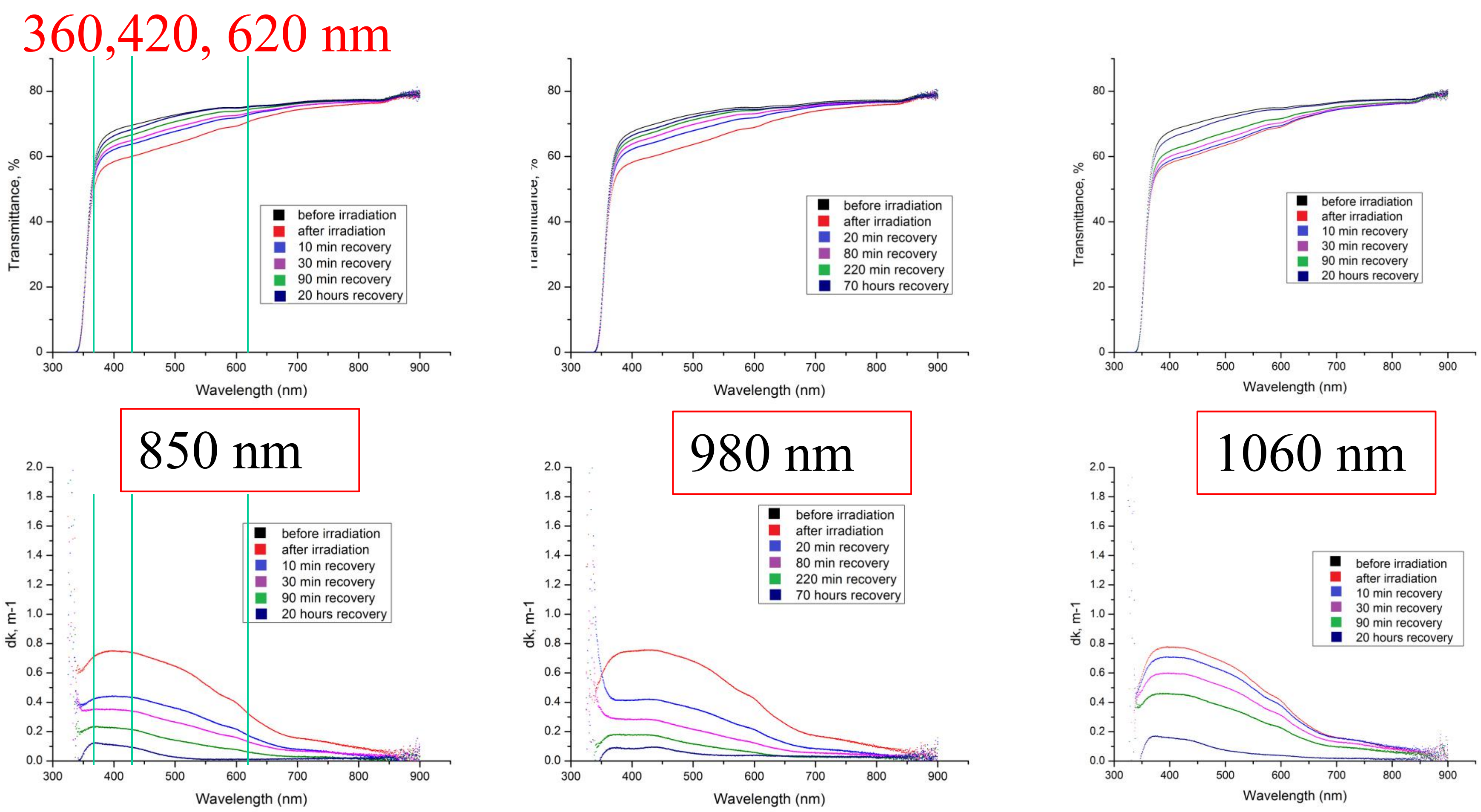






- Test with set of laser diodes were done: 462, 850, 980, 1060 and 1310 nm
- The intensity of laser diodes was measured by optical power meter for whole system (include optical fibers)

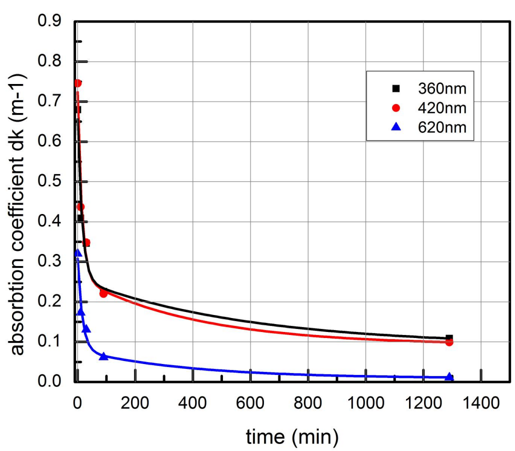
Recovery spectra of the transmittance and dk @ RT



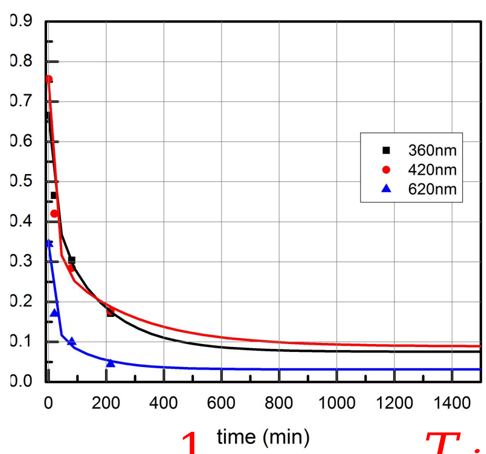
- Recovery of dk measured at 360, 420 and 620 nm @RT.
- The illumination with laser diodes: 850 nm, 980 nm, 1060 nm

Light illumination by:

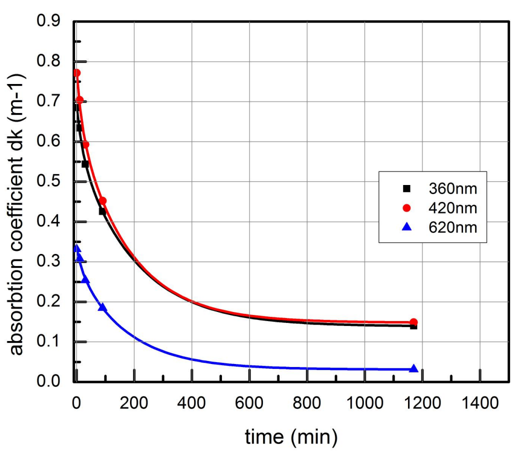
850 nm



980 nm



1060 nm

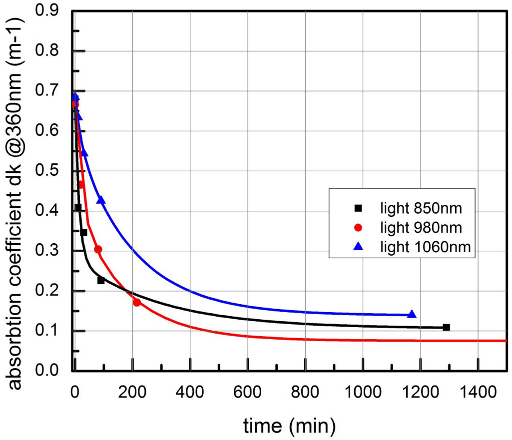


$$dk = \frac{1}{l} * \ln\left(\frac{T_{int}}{T_{after}}\right)$$

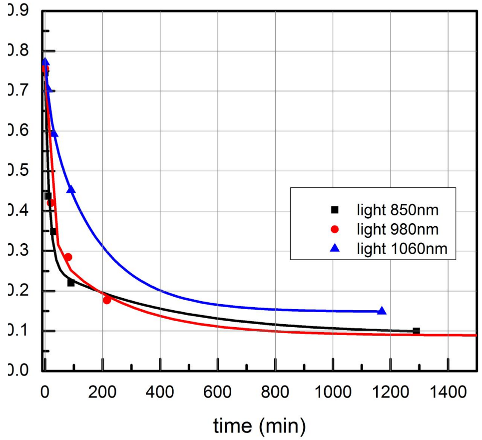
- Recovery of dk measured at 360, 420 and 620 nm @RT.
- The illumination with laser diodes: 850 nm, 980 nm, 1060 nm

Absorbtion coefficient at:

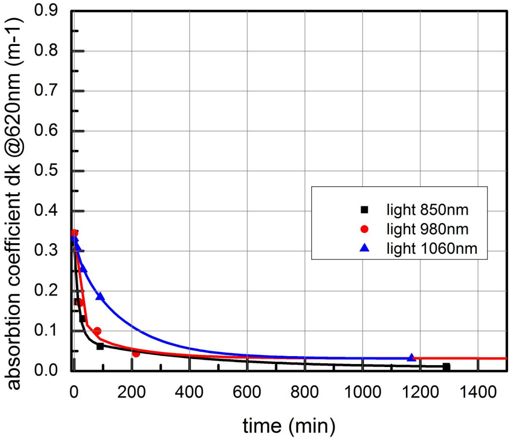
360 nm



420 nm

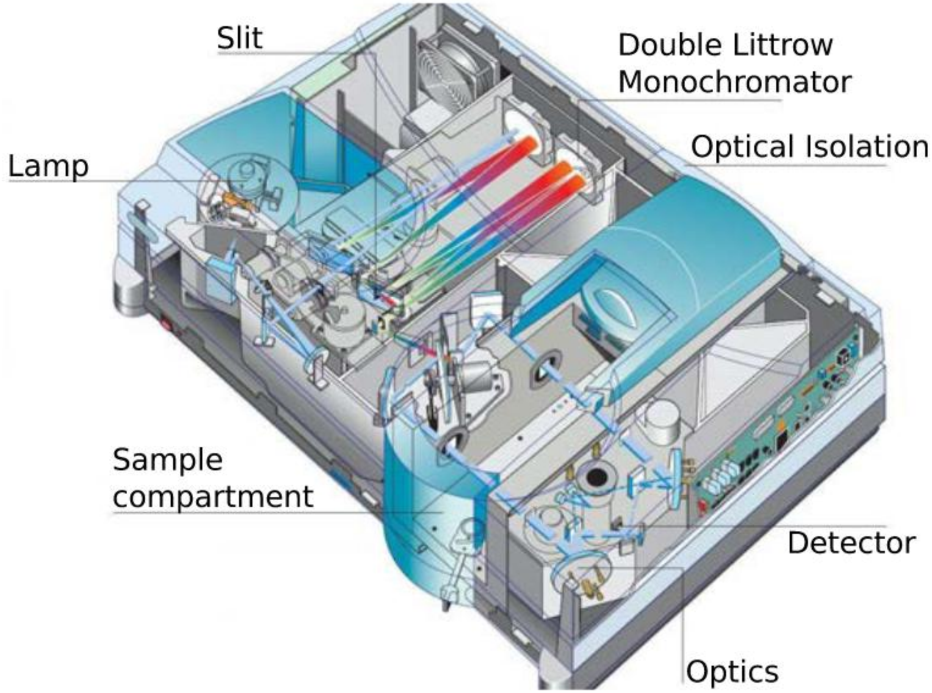


620 nm

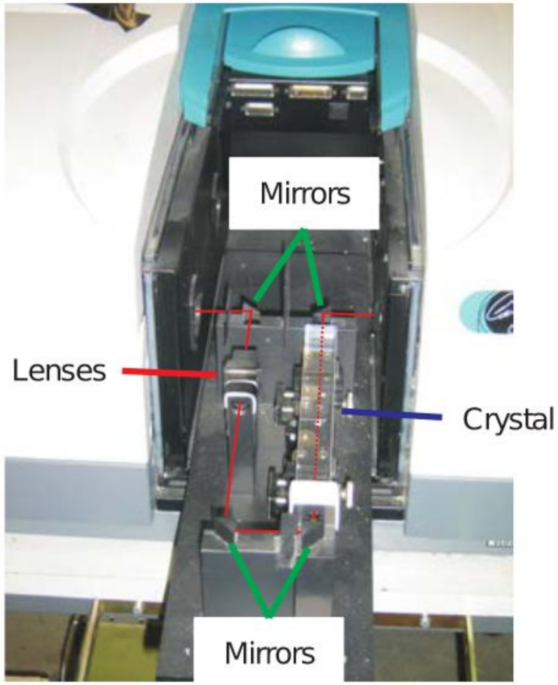


Longitudinal transmission

- VARIAN spectrometer - conventional double beam spectrometer
- A special optics setup (Fig. 2.13b) consisting of mirrors and lenses has to be adapted to the spectrometer, so that the light can be guided almost perfectly parallel across the full length of the crystal..



(a) Photo spectrometer.



(b) Additional optics by [29].

Figure 2.13: *VARIAN* spectrometer.