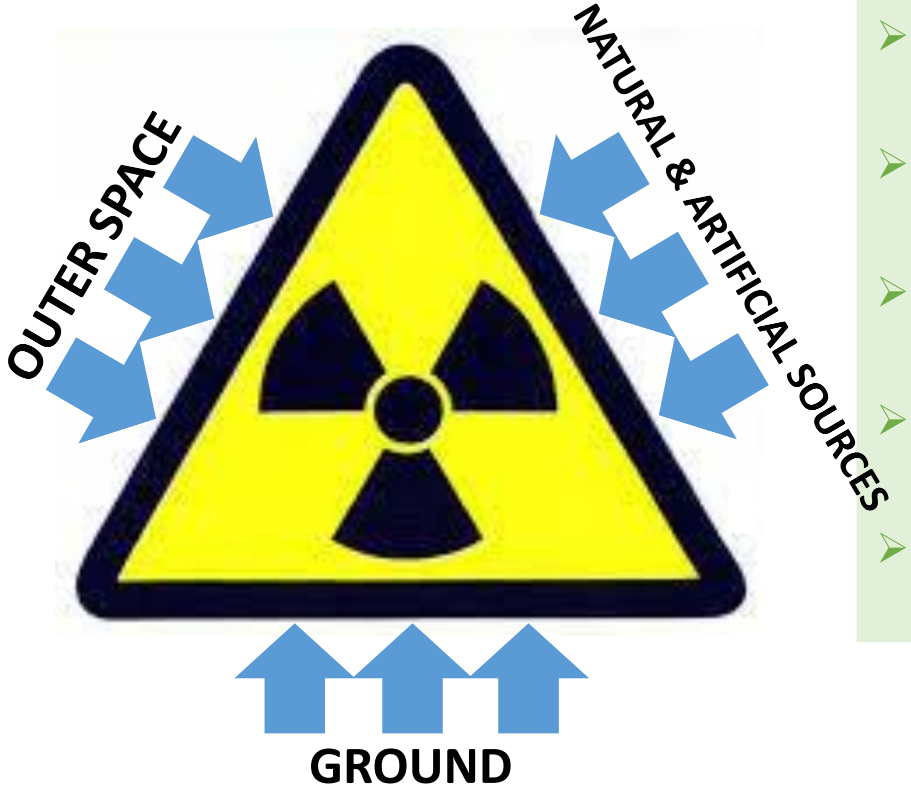
LiMgPO$_4$:RE

review of the results of 7-years investigations on new dosimetric crystals

Wojciech Gieszczyk
Radiation Physics and Dosimetry Department
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

My research activities – passive dosimetry of ionizing radiation

Ionizing radiation is all around us



Need for dosimetric measurements:

- Personal dosimetry
- Environmental monitoring
- Medical applications
- Industrial applications
- Nuclear physics experiments

My research activities – passive dosimetry of ionizing radiation

How to measure the energy delivered by ionizing radiation

Ionizing radiation is all around us

Need for dosimetric measureme

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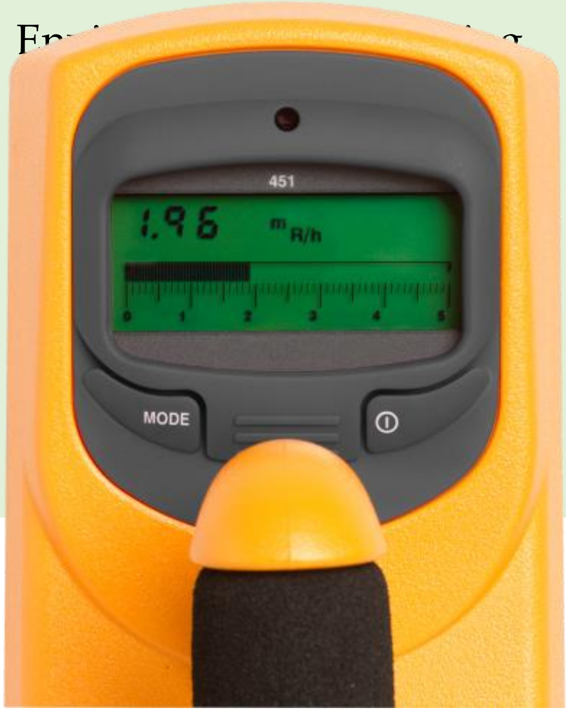
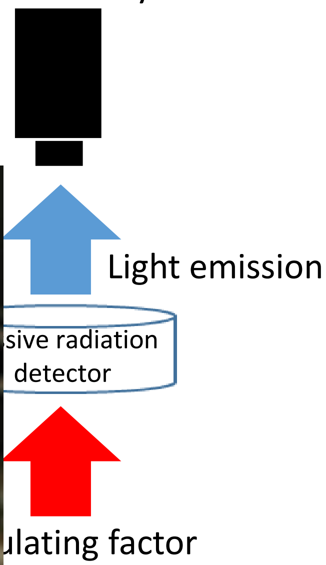
- En



MATERIAL

METHOD


α β γ n

Introduction

My research activities – passive dosimetry of ionizing radiation

How to measure the energy delivered by ionizing radiation

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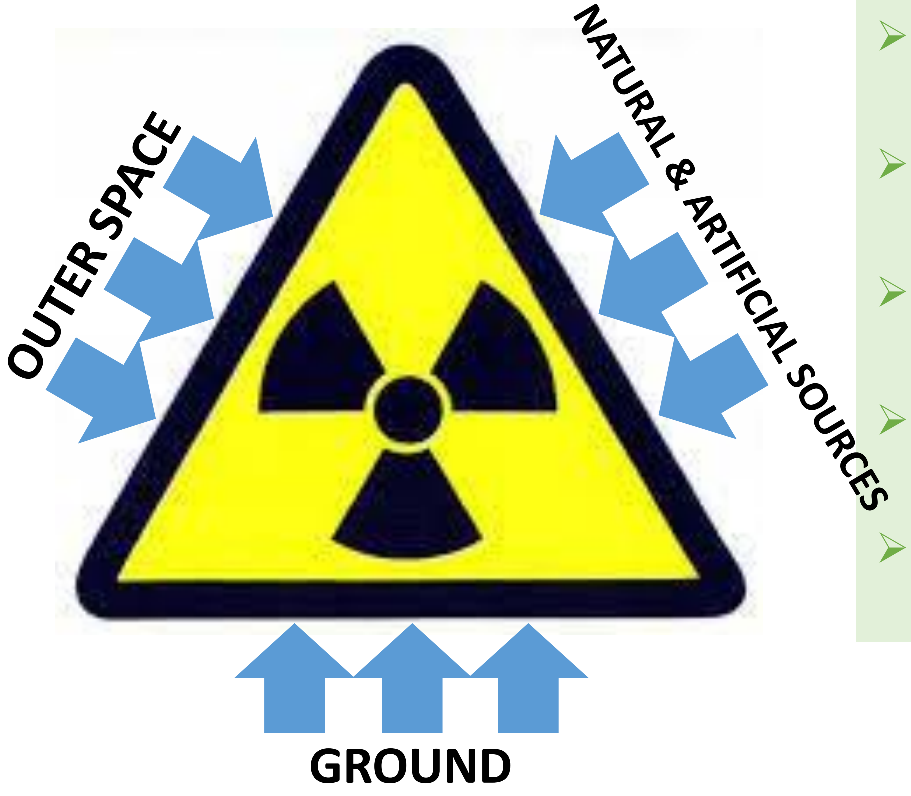

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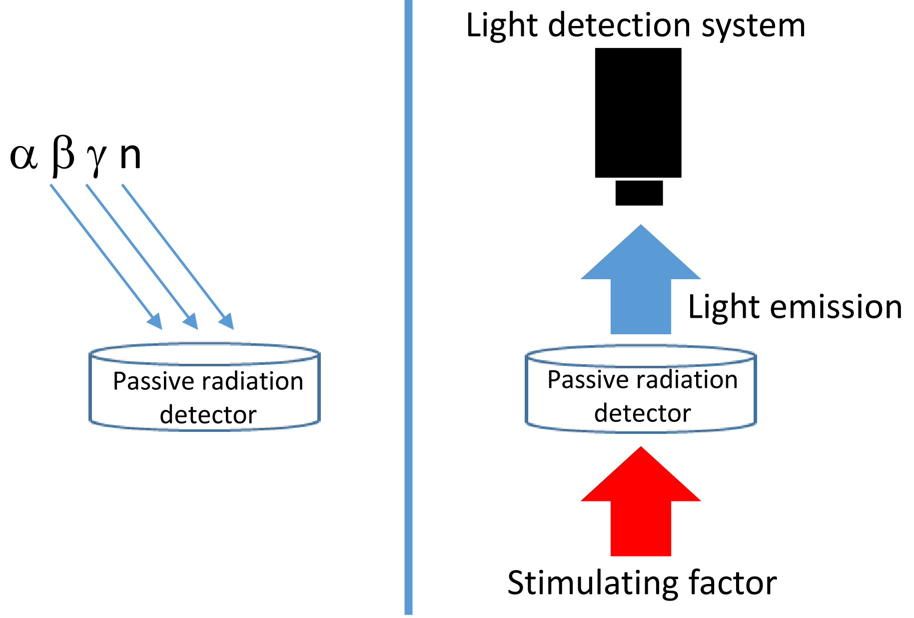


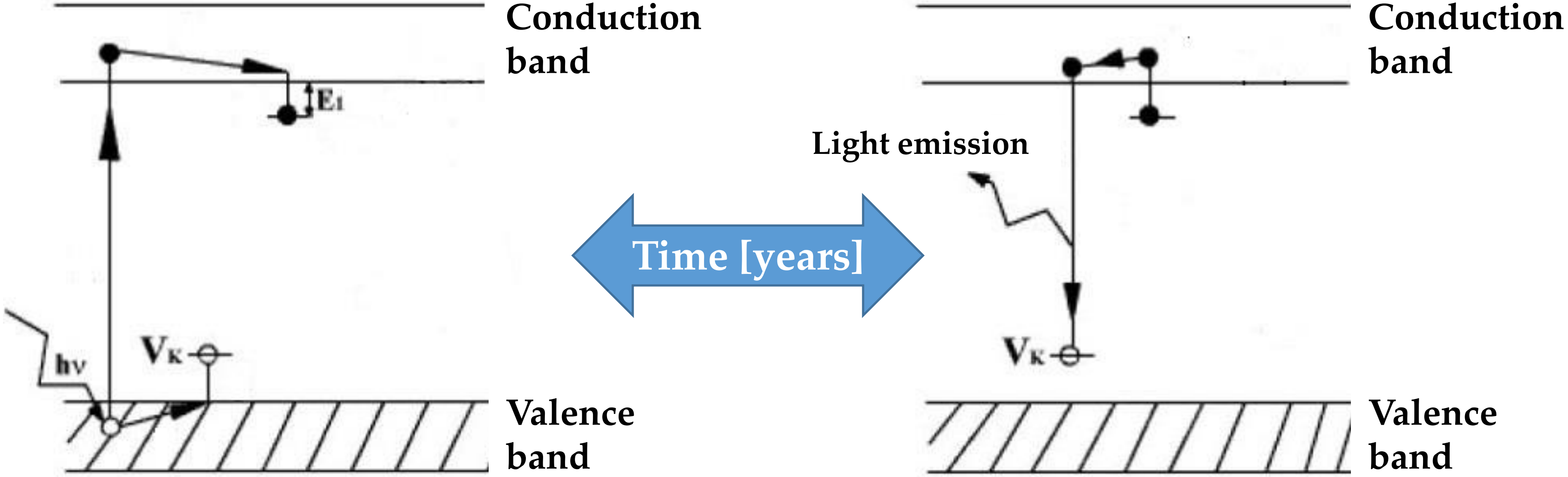
Stimulated luminescence phenomena: 2-stage processes

- Thermally Stimulated Luminescence (TSL, TL) – still most popular
- Optically stimulated Luminescence (OSL) – becomes more widely applied measurement technique

Simplified model

1st stage – absorption of radiation energy

2nd stage – stimulation associated with light emission

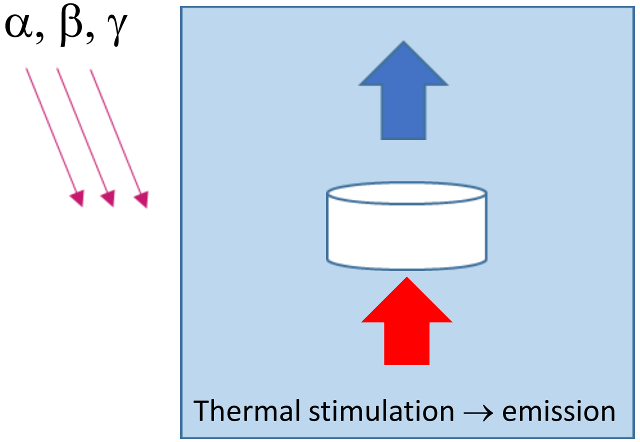


Introduction

Stimulated luminescence phenomena

Ionizing radiation (any kind)

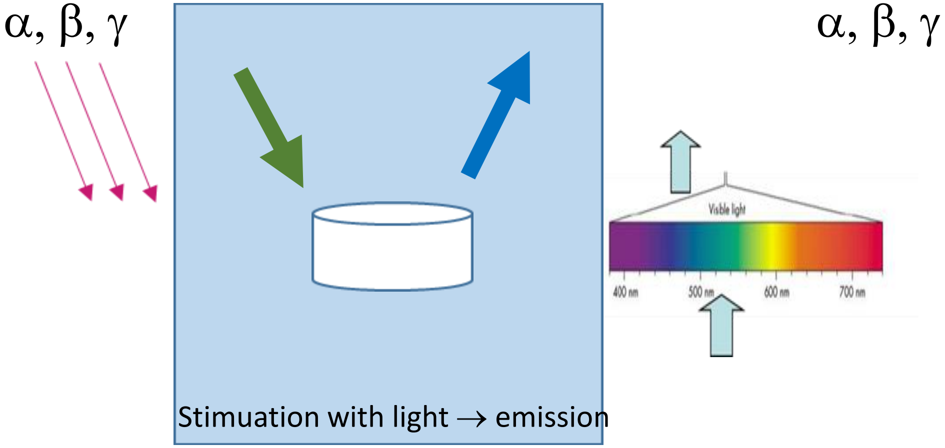
α, β, γ



TL

Ionizing radiation (any kind)

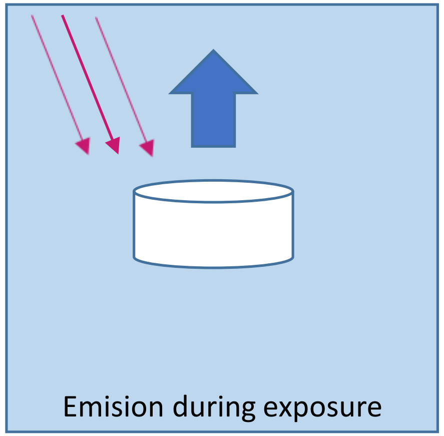
α, β, γ



OSL

Ionizing radiation (any kind)

α, β, γ



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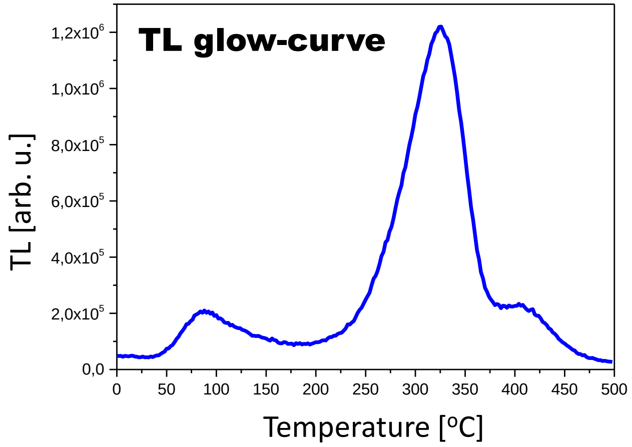

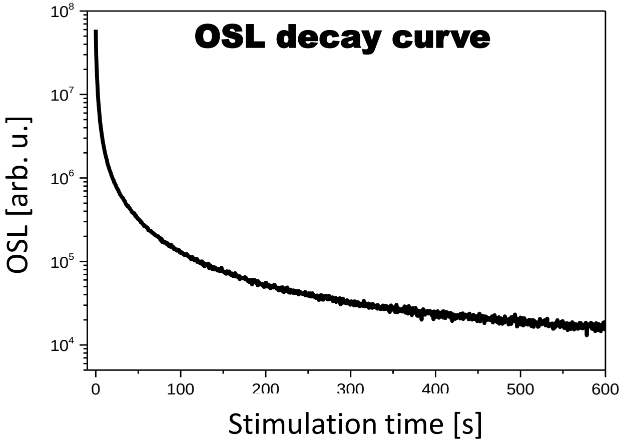

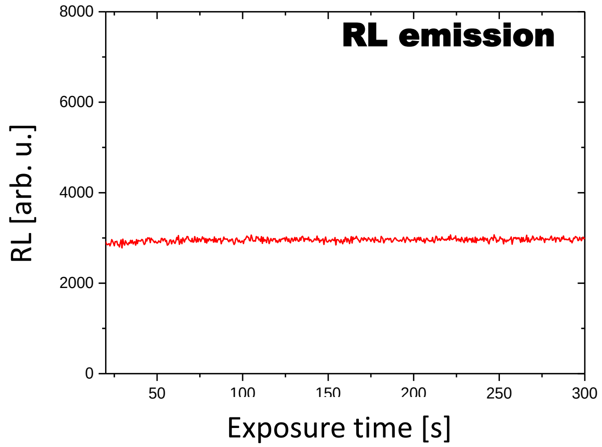

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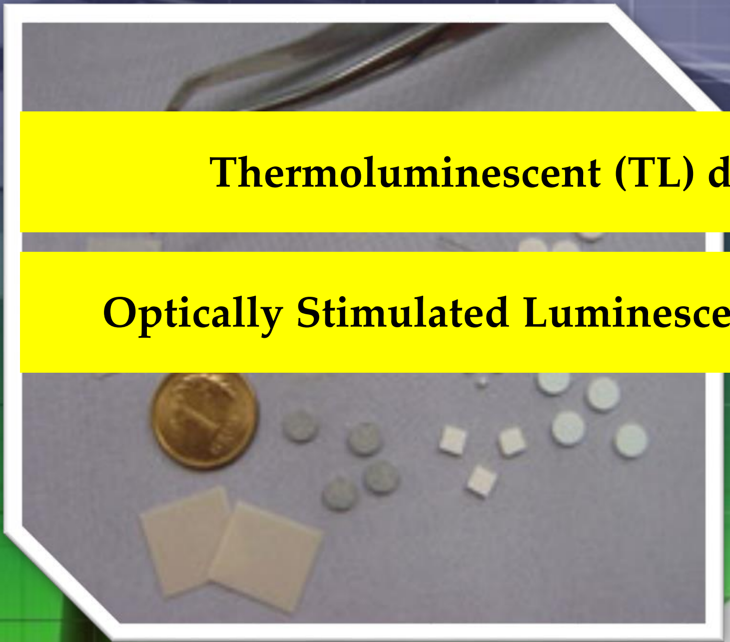
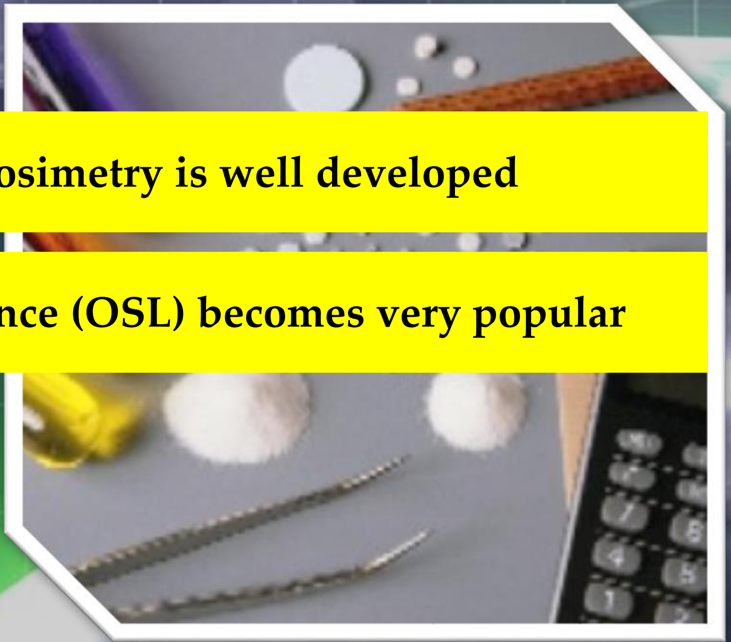




Thermoluminescent (TL) dosimetry is well developed

Optically Stimulated Luminescence (OSL) becomes very popular

Widely used TL materials

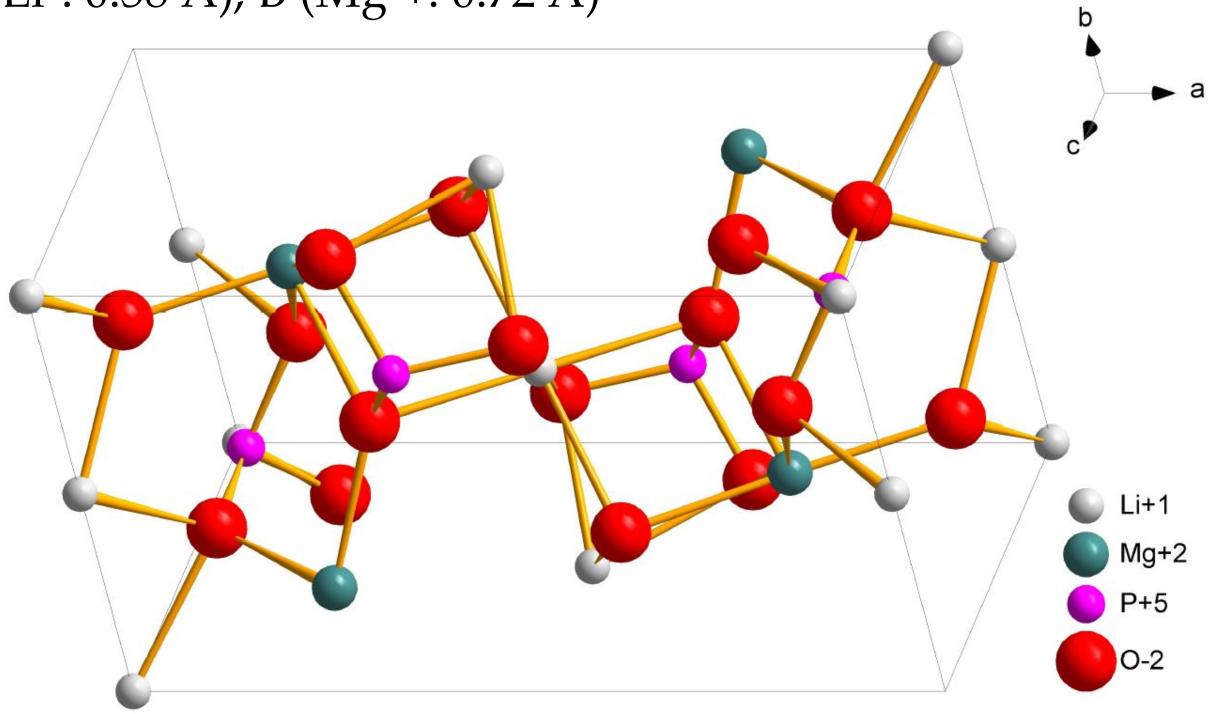
- **LiF**
- **CaF_2**
- **$CaSO_4$**
- **Mg_2SiO_4**
- **$Li_2B_4O_7$**
- **Al_2O_3**
- **BeO**
- **$LiMgPO_4$???**

OSL materials

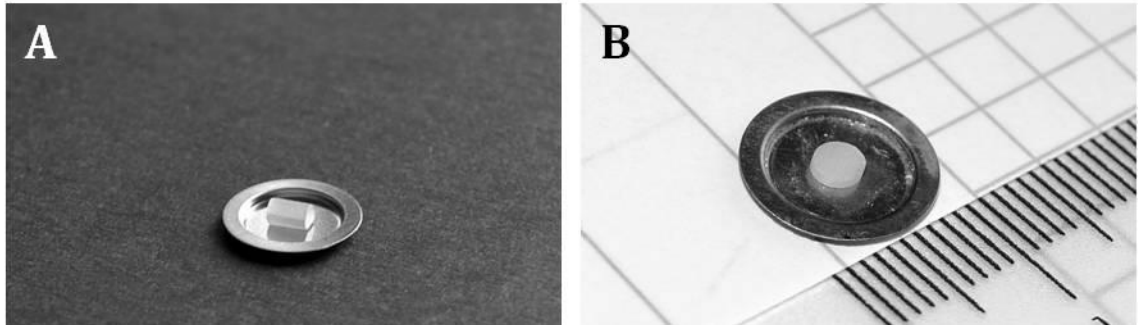
- **Al_2O_3**
- **BeO**
- **$LiMgPO_4$???**

Basic data on LMP compound

Orthophosphate of $ABPO_4$ formula
A (Li^{+}: 0.58 Å), B (Mg^{2+}: 0.72 Å)



3D crystal structure of $LiMgPO_4$ prepared by Diamond 4.1 software using the data from Crystallographic Open Database (COD 1530053) View towards the <h,k,l> = <1,1,1> plane



Exemplary LMP crystals placed on stainless-steel cups

Property	Value
Crystallographic system	Orthorhombic
Space group	Pnma
Unit cel parameters	a = $10.147 \cdot 10^{-10}$ m
	b = $5.909 \cdot 10^{-10}$ m
	c = $4.692 \cdot 10^{-10}$ m
Unit cel volume	$281.32 \cdot 10^{-30}$ m^3
Molar mass	126.225 g/mol
Density	2.98 g/cm^3
Effective atomic numer (Z_{eff})	11.5
$Z_{eff\ Al2O3}$	11.4
$Z_{eff\ LiF}$	8.2
$Z_{eff\ BeO}$	7.2
$Z_{eff\ tissue}$	7.4

Olivine-type structure stable over a broad temperature range

W. Gieszczyk, B. Marczewska, M. Kłosowski, A. Mrozik, P. Bilski, A. Sas-Bieniarz, P. Goj, P. Stoch. **Materials 12 (2019), 2861**

Materials & Methods

New material developed and optimized in IFJ PAN in Krakow

Samples preparation techniques (powders)

Solid-state reaction betwen:

- lithium hydroxide (LiOH)
- hexahydrate magnesium nitrate ($Mg(NO_3)_2 \cdot 6H_2O$)
- ammonium dihydrogen phosphate ($NH_4H_2PO_4$)

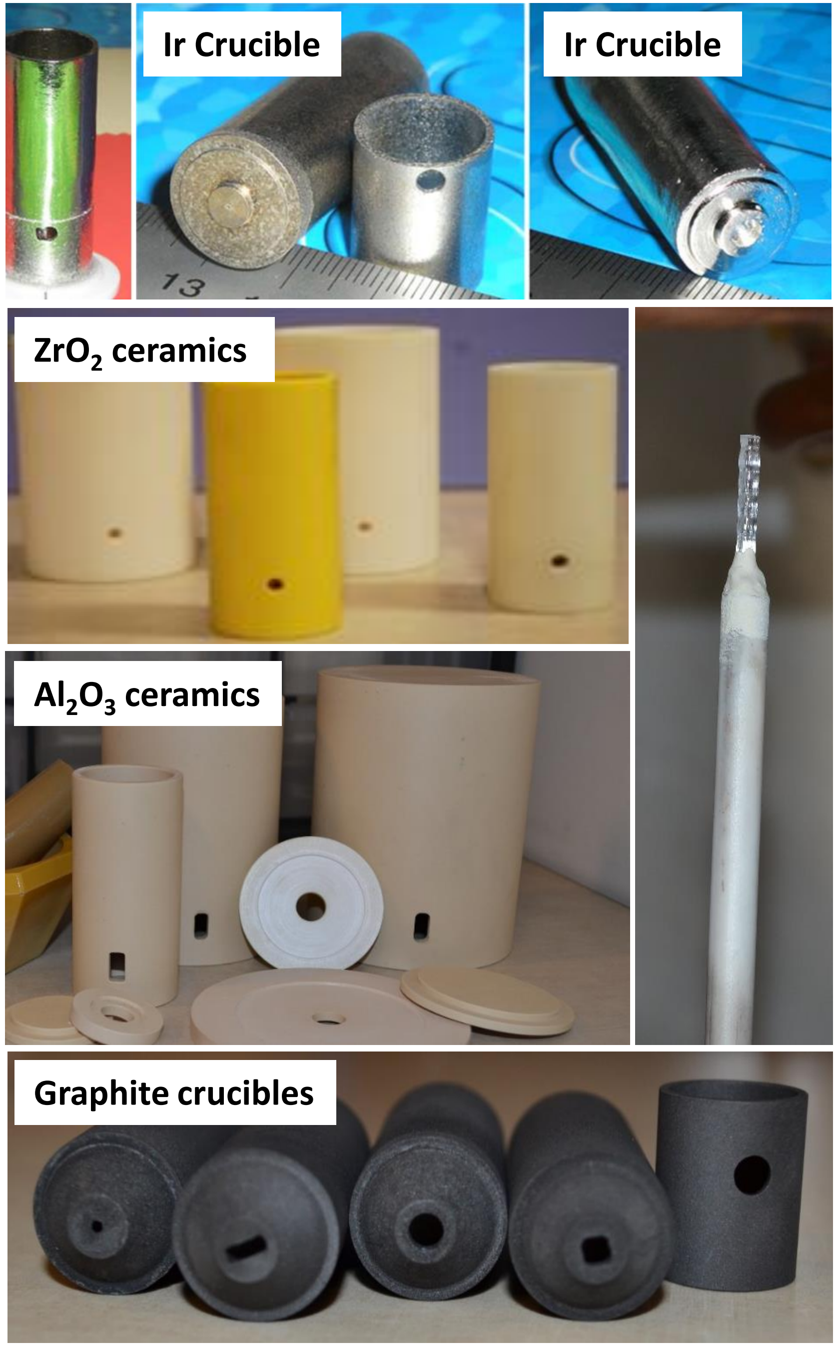
$$2LiOH + 2Mg(NO_3)_2 \cdot 6H_2O + 2NH_4H_2PO_4 \xrightarrow{\Delta T} 2LiMgPO_4 + 2NH_3 + 4NO_2 + 16H_2O + O_2$$

- followed by several annealing cycles at the temperatures ranging from 200 to 750 ^{o}C

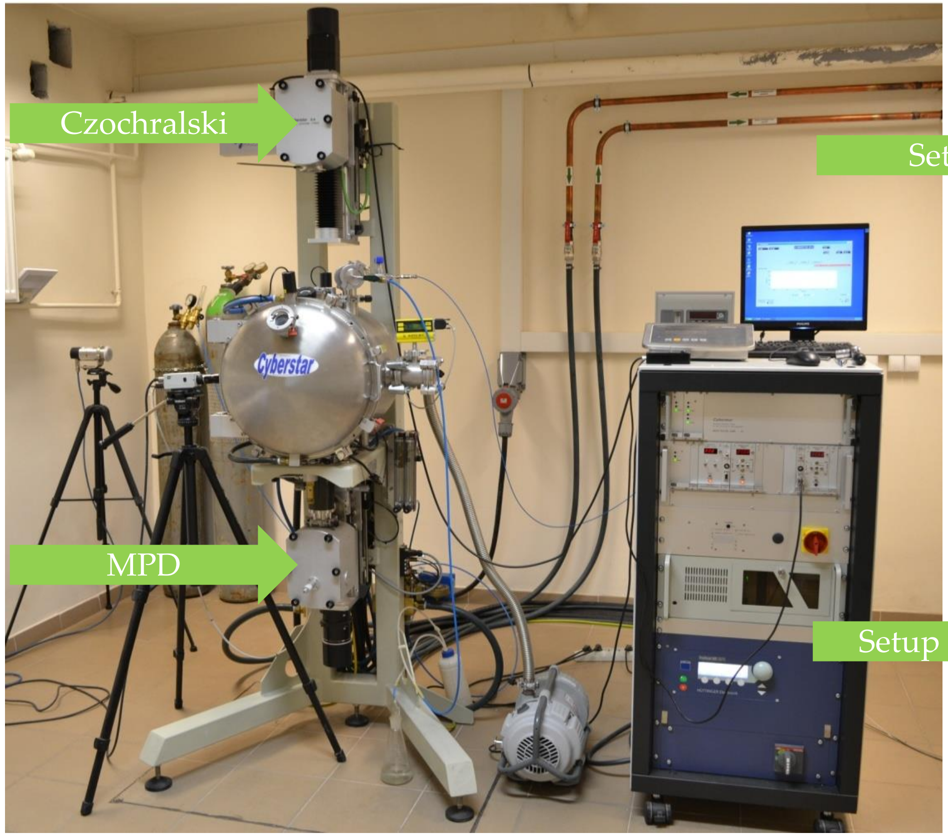
We are probably the first research group that developed and optimized this material in the form of **melt-grown crystals**

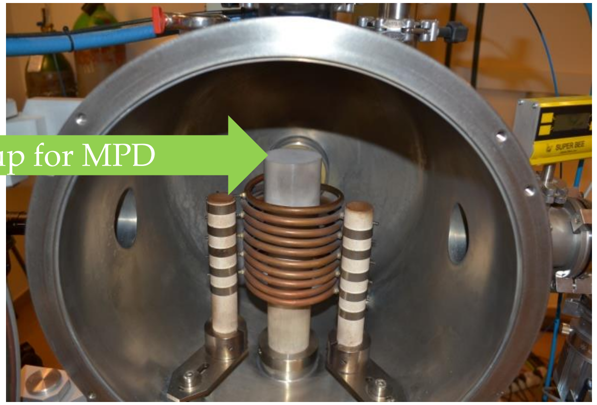
Materials & Methods

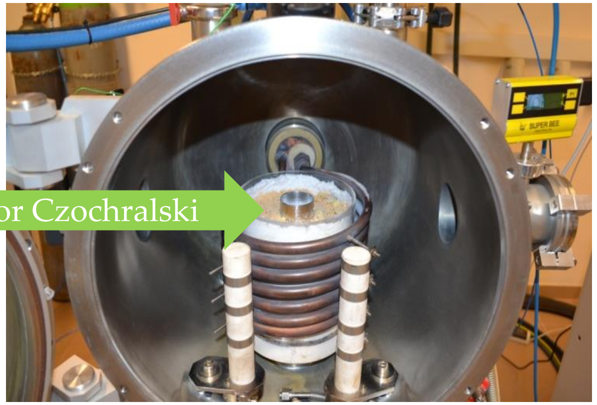
Thermal setup elements:



Samples preparation techniques (crystals)



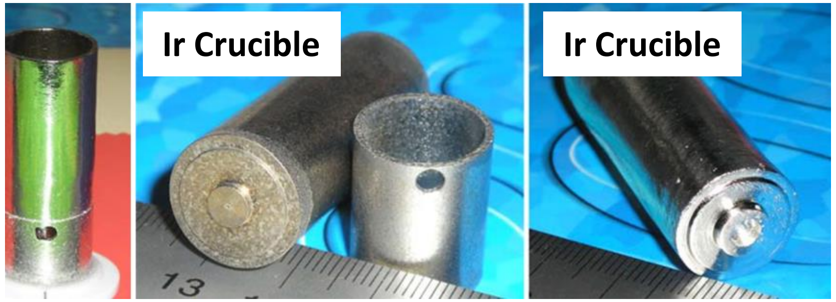




- Inductive furnace made by Cyberstar (France)
- Middle-frequency generator of 20 kW power
- Achievable temperatures above 2000 ^{o}C
- Two methods of crystal growth in one device (micro-pulling-down, µPD and Czochralski)

Materials & Methods

Thermal setup elements:



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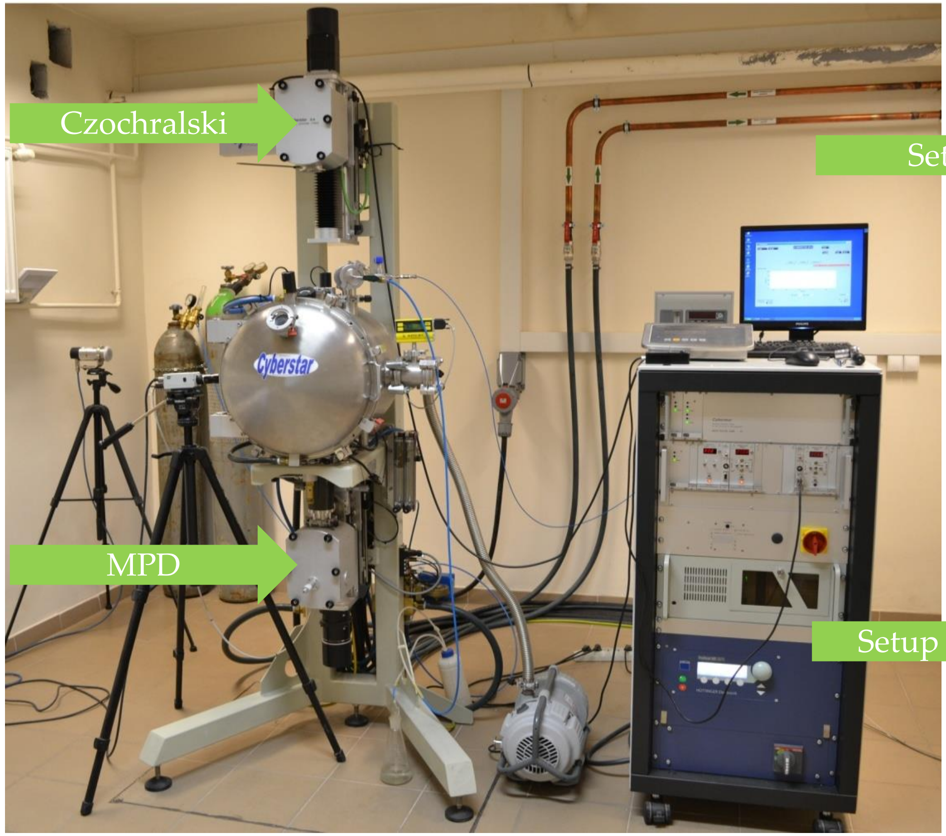
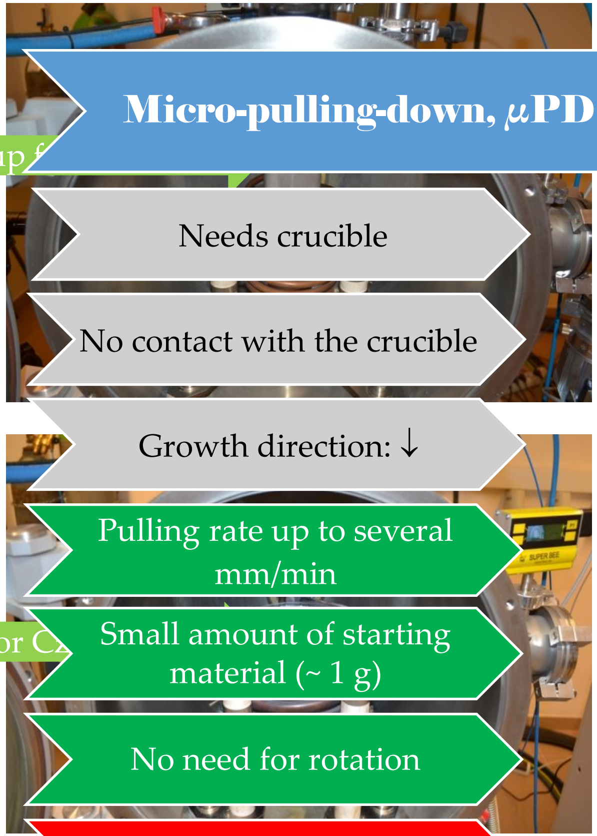
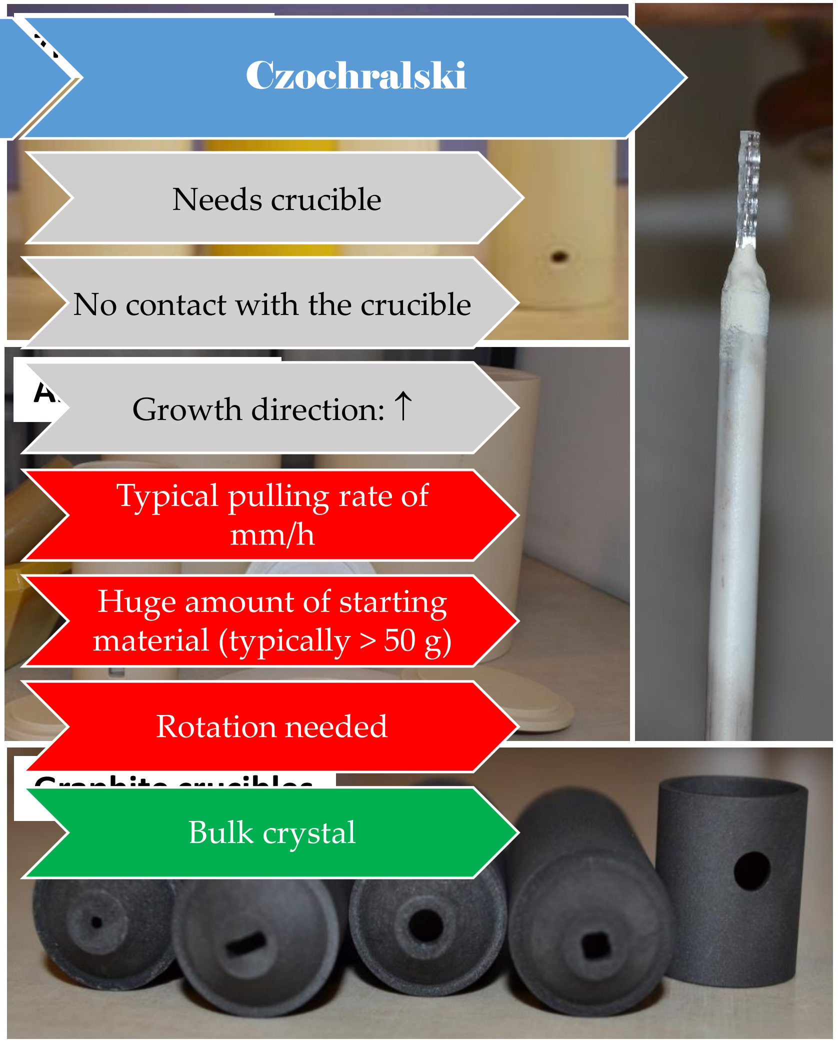


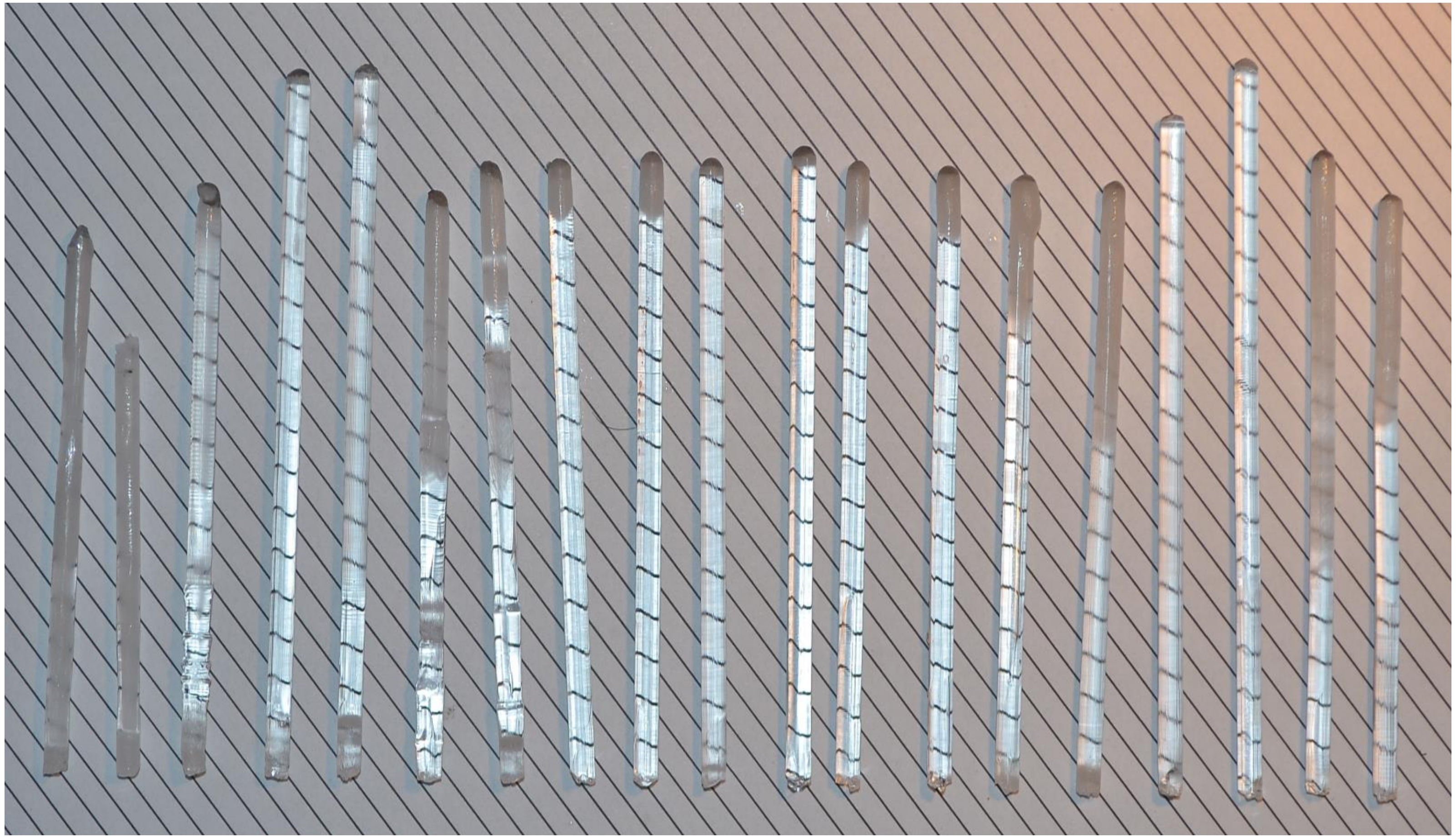




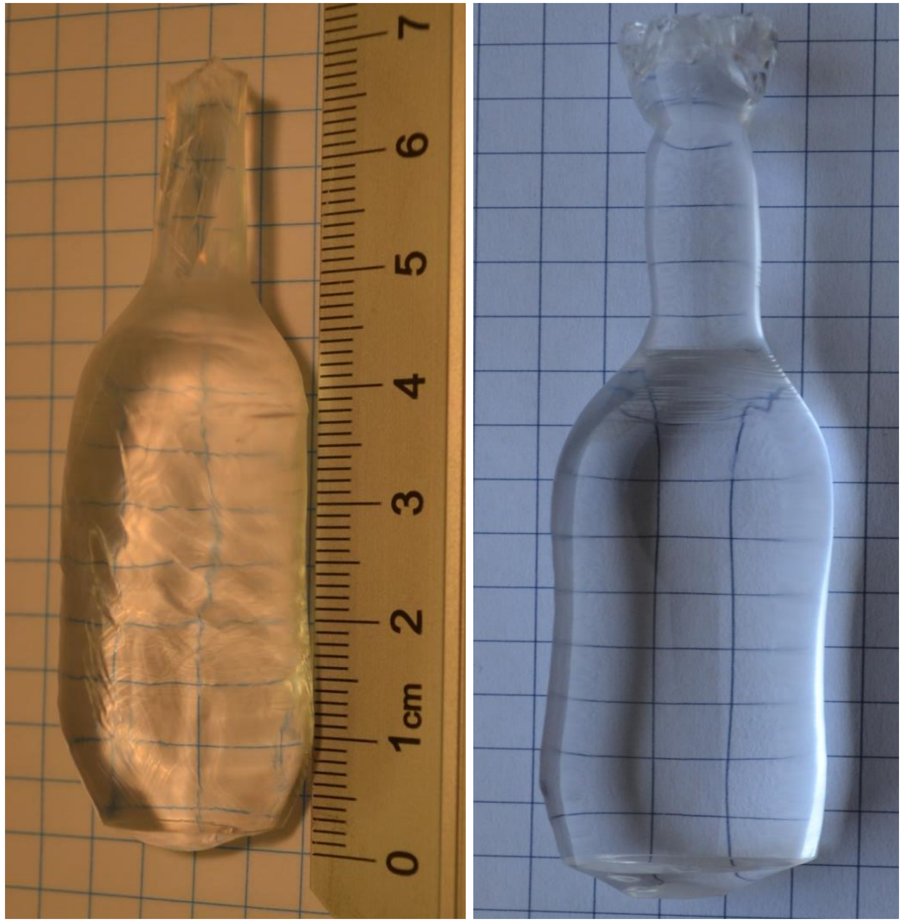
Micro-pulling-down, μPD	Czochralski
Needs crucible	Needs crucible
No contact with the crucible	No contact with the crucible
Growth direction: ↓	Growth direction: ↑
Pulling rate up to several mm/min	Typical pulling rate of mm/h
Small amount of starting material (~ 1 g)	Huge amount of starting material (typically > 50 g)
No need for rotation	Rotation needed
Rod-shape crystals	Bulk crystal

- Inductive furnace made by Cyberstar (France)
- Middle-frequency generator of 20 kW power
- Achievable temperatures above 2000 °C
- Two methods of crystal growth in one device (micro-pulling-down, μPD and Czochralski)

Samples preparation techniques (crystals)



Series of our LiF crystals obtained by micro-pulling-down method



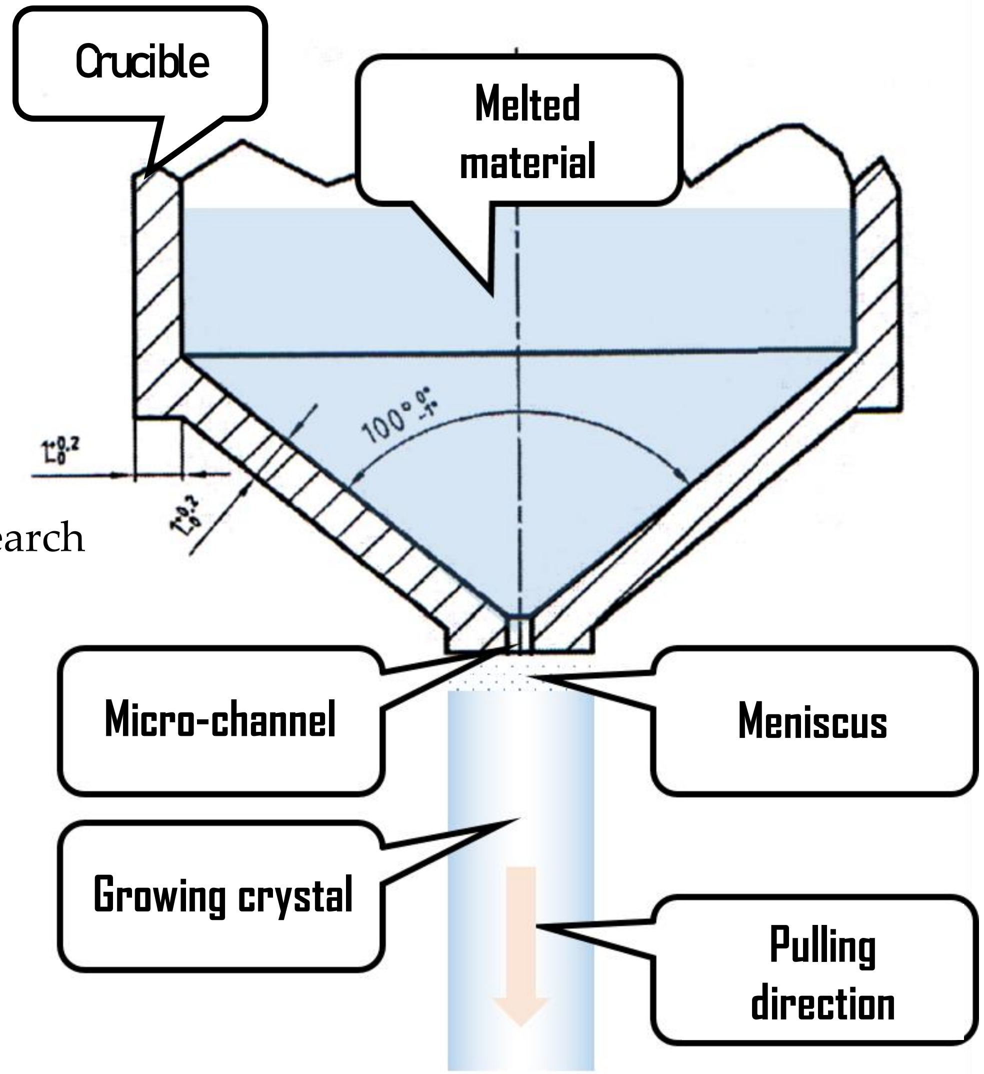
Our LiF crystals obtained by Czochralski method

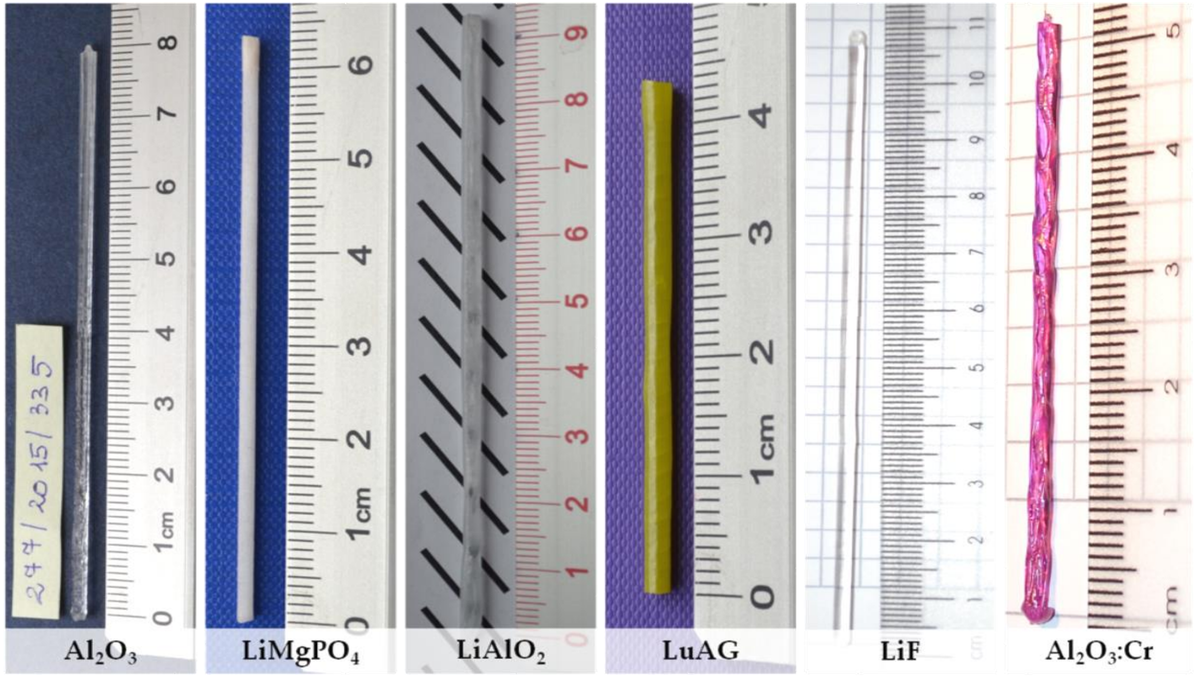
Materials & Methods

Samples preparation techniques (crystals)

Micro-Pulling-Down method:

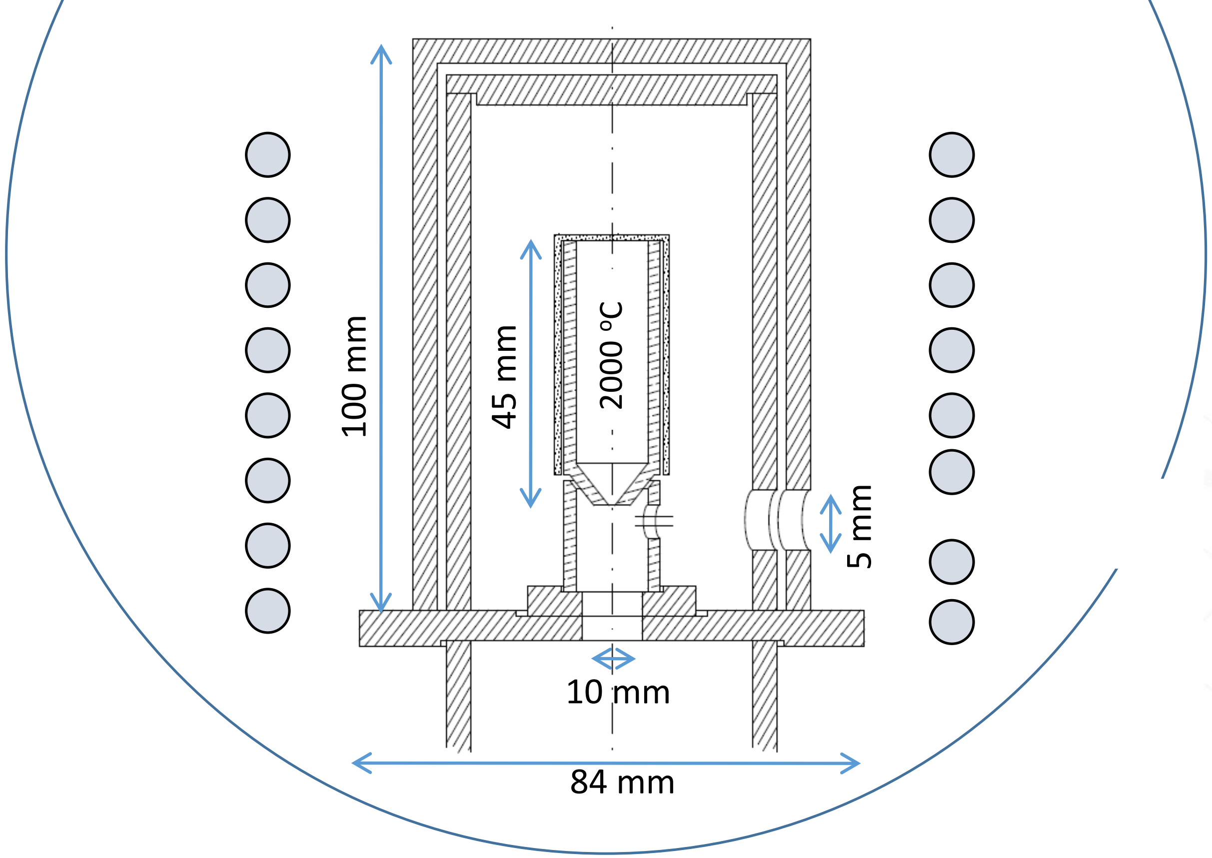
- High-temperature growth (even above 2000 °C for selected materials)
- Needs a dedicated crucible made of noble metal
- Fast and cheap method for crystal growth for the needs of laboratory research

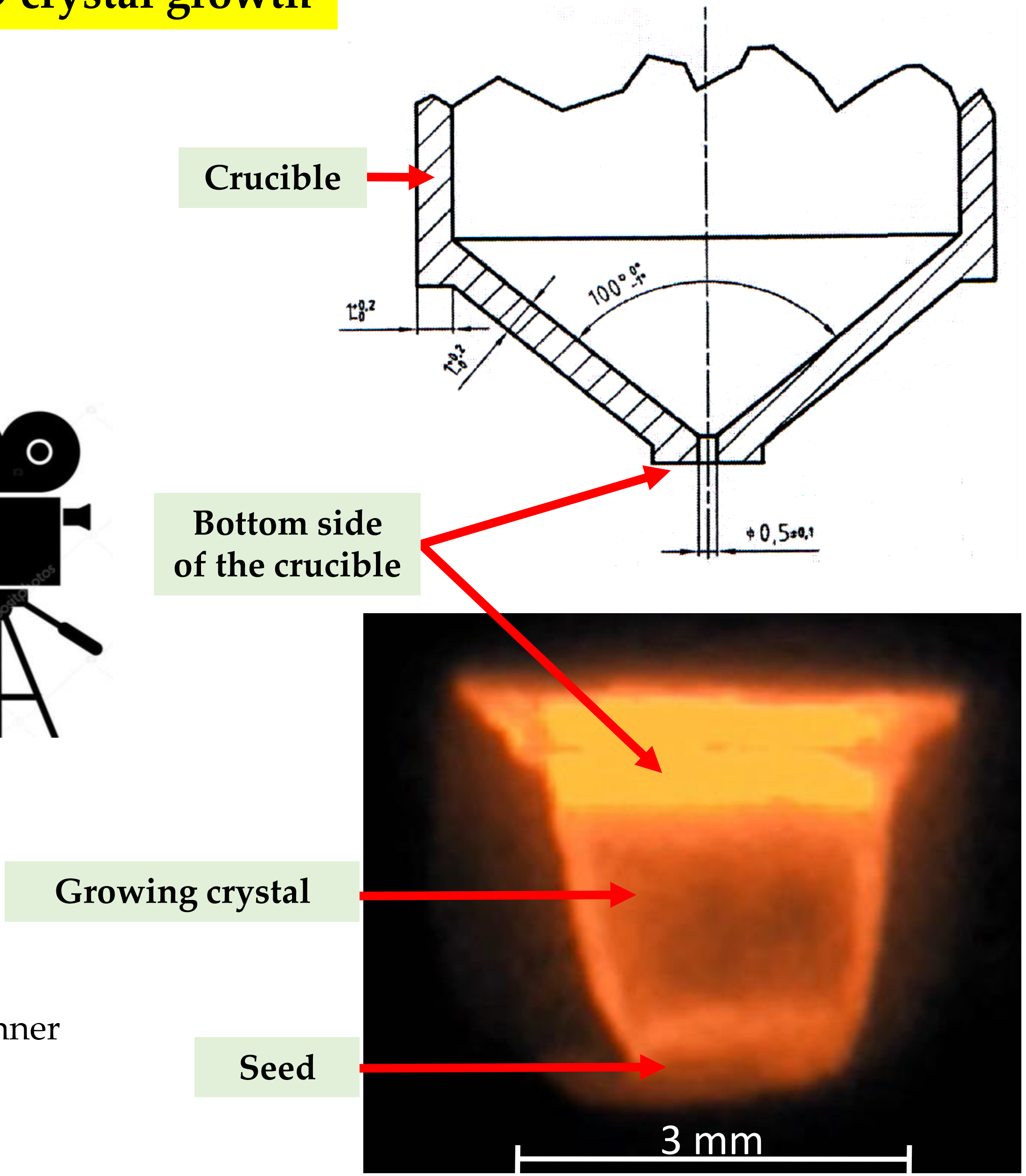




Materials & Methods

Challenges for MPD crystal growth



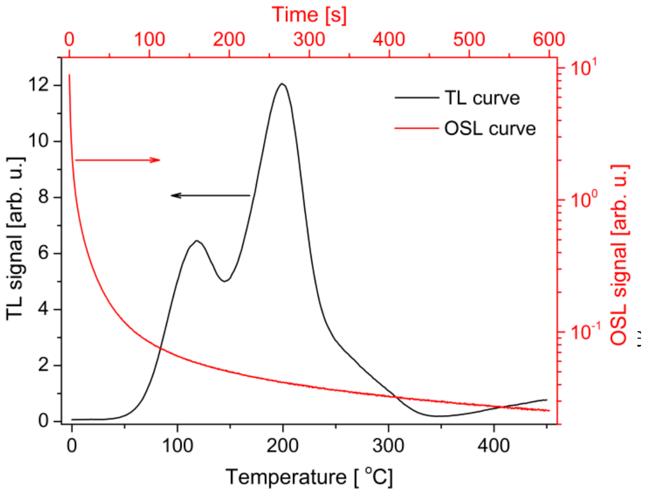


- Precise set of the relatively small thermal setup elements
- Lack of permanent fastening of thermal setup elements
- Not possible to run the process without a live view
- Melted material must flow through the micro channel in a controlled manner
- Stable contact of the seed with the melted material is needed
- Adequate temperature gradient needed for stable growth
- The crucible cleaning problems

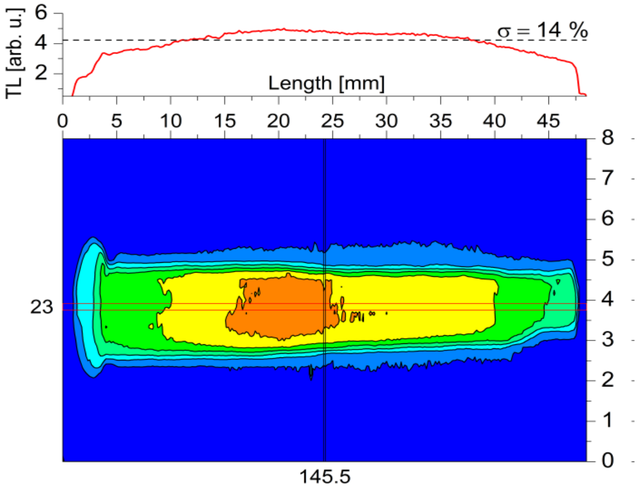
Materials & Methods

Devices applied for the measurements of TL(T), OSL(t), TL(λ), CL(λ)

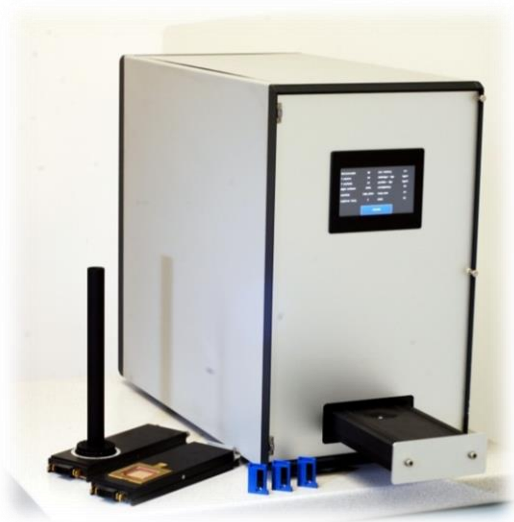
TL/OSL measurements

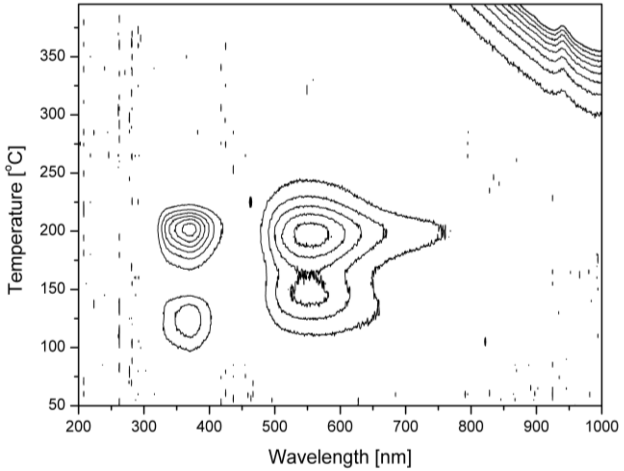


2D-TL measurements

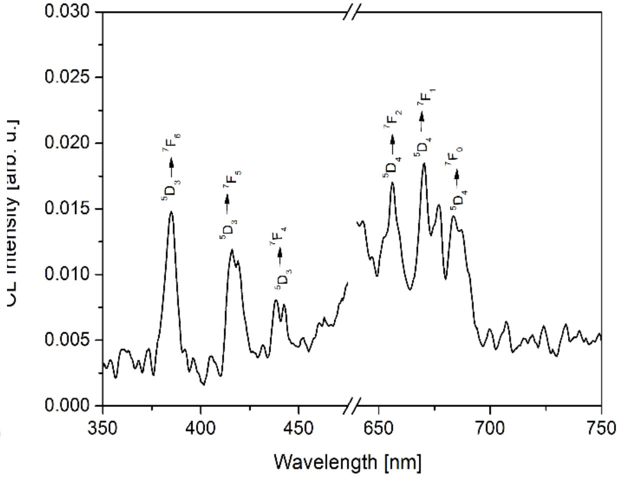


Spectral measurements





CL measurements



Materials & Methods

Overview of crystal growth experiments

Matrix	Dopant	Doping strategy	Dopant concentration	Crucible material	Hot zone material	Protective atmosphere	Pulling rate
$LiMgPO_4$	Tb B Tm Eu Er Y Gd Sm Yb	No doping or Single doping or Double doping or Triple doping	0.1 – 10 mol%	Ir Mo C	ZrO_2 Al_2O_3	Ar Ar/H_2	0.03 – 5.0 mm/min

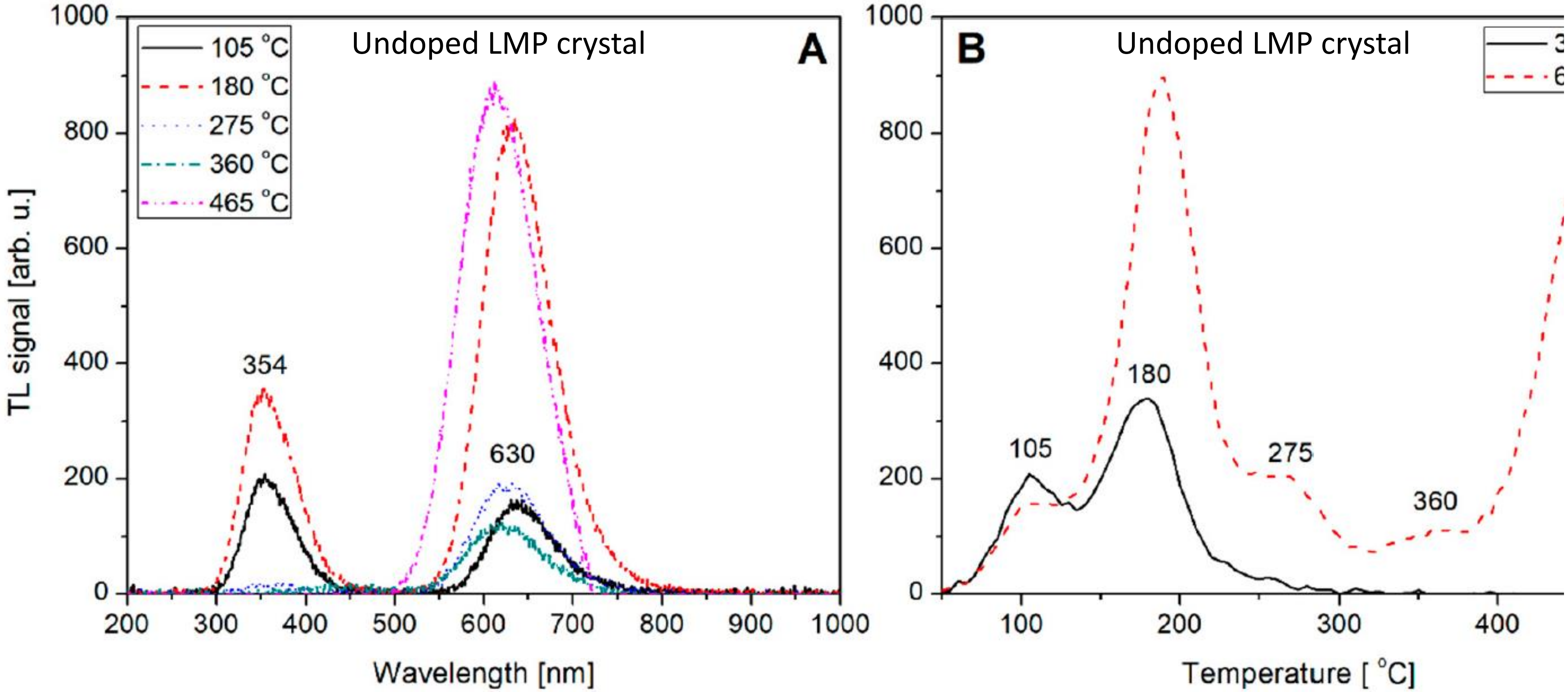
1 crystal/day with MPD

1 crystal/day with MPD method
1 crystal/week with Czochralski method

More than 100 different LMP crystals investigated within this work

TL emission of LMP crystals

Short-wavelength emission is better for TL measurements



Undoped LMP crystal: Two broad emission bands: 354 and 630 nm – the emission of F^+ and F centers

In **Tm-doped crystal** all transitions characteristic for Tm ions visible and the emission is strongly shifted towards higher temperatures

W. Gieszczyk, B. Marczewska, M. Kłosowski, A. Mrozik, P. Bilski, A. Sas-Bieniarz, P. Goj, P. Stoch. **Materials 12 (2019), 2861**

Results

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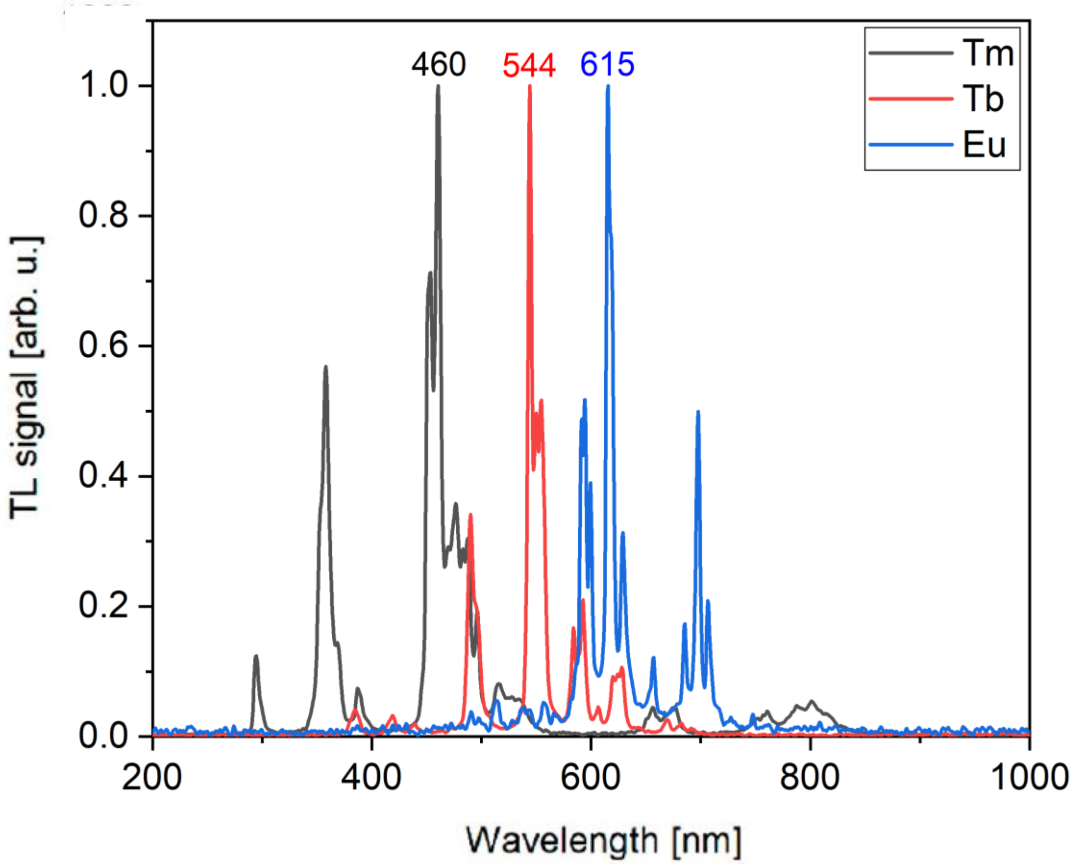

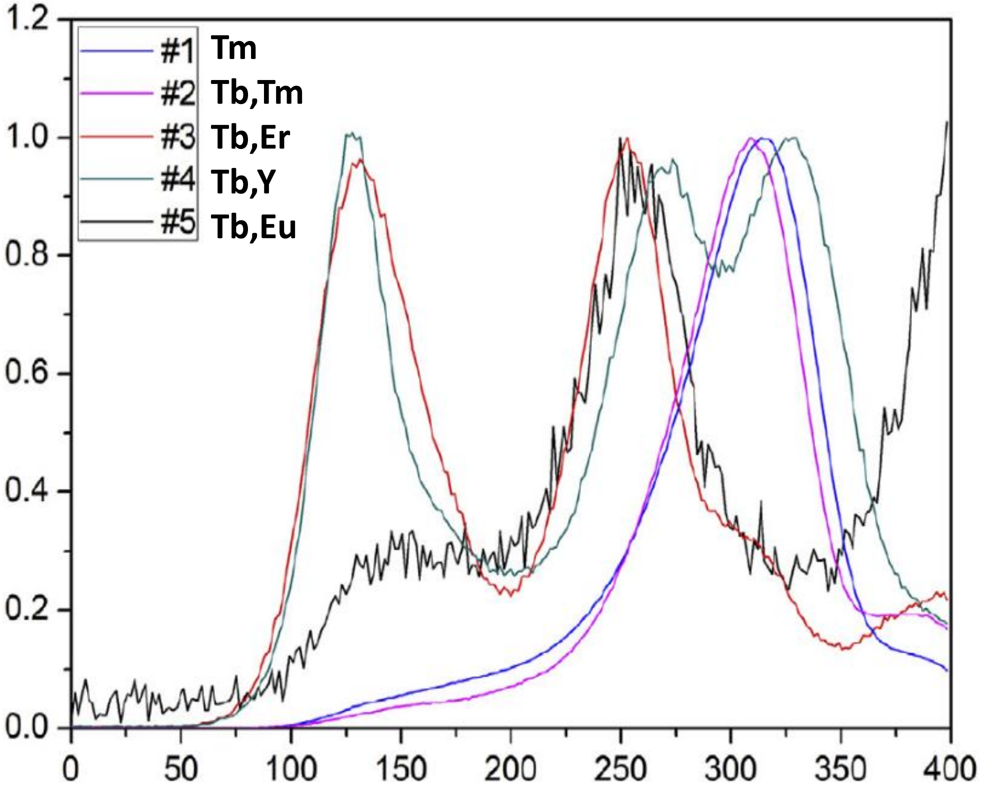

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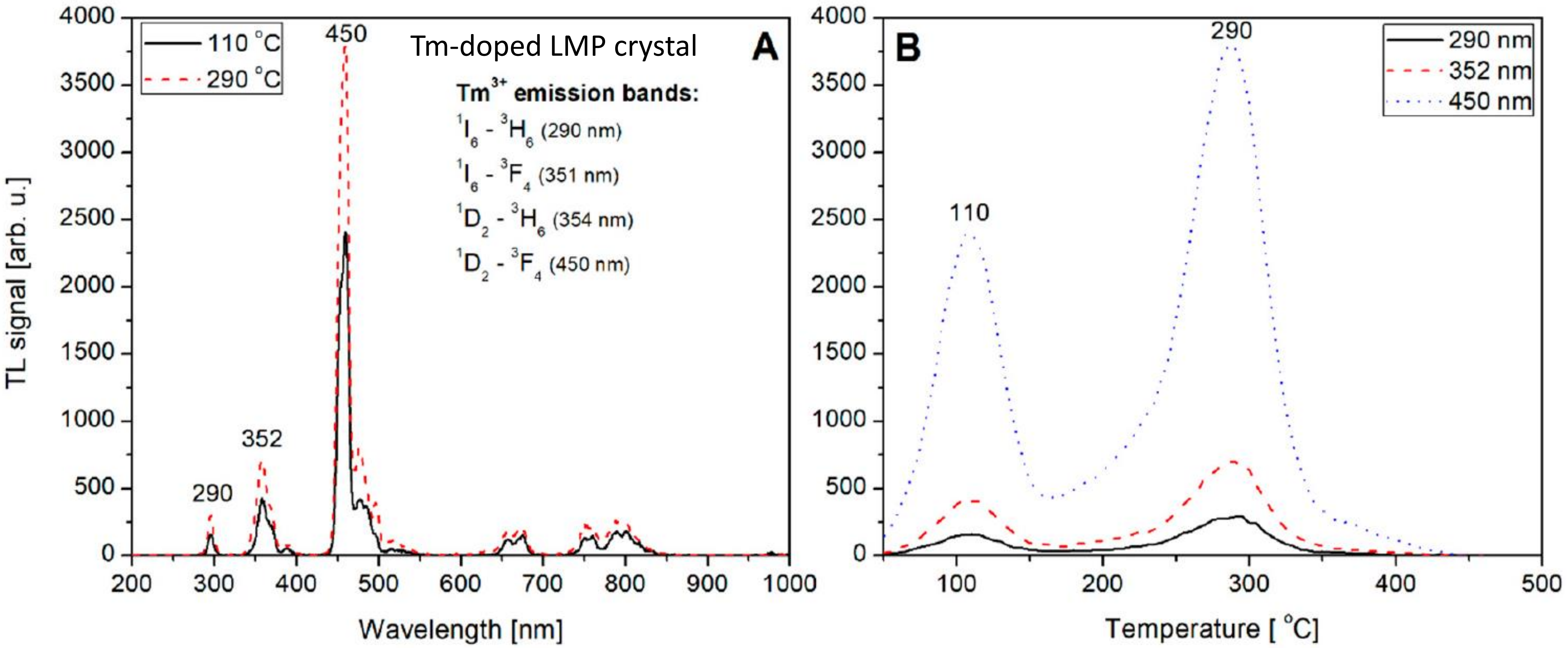

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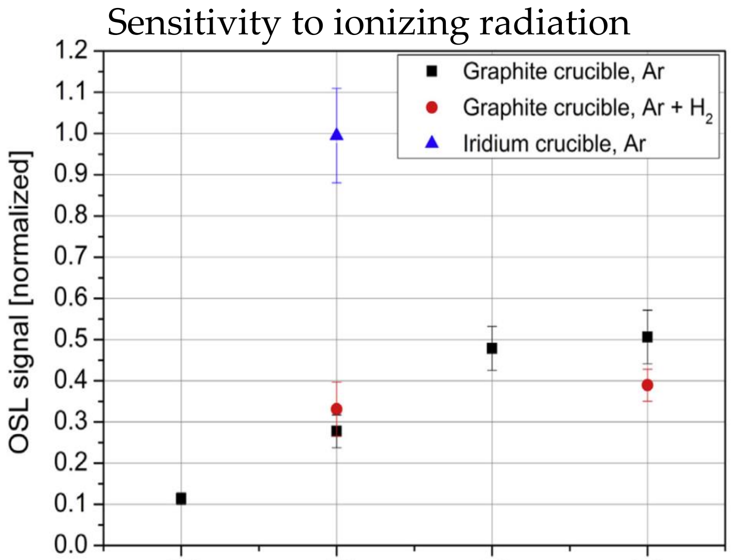
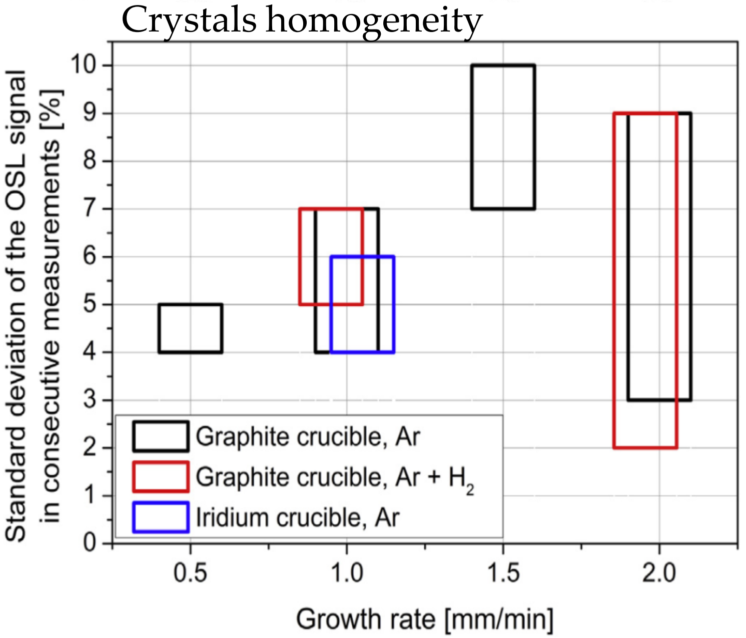
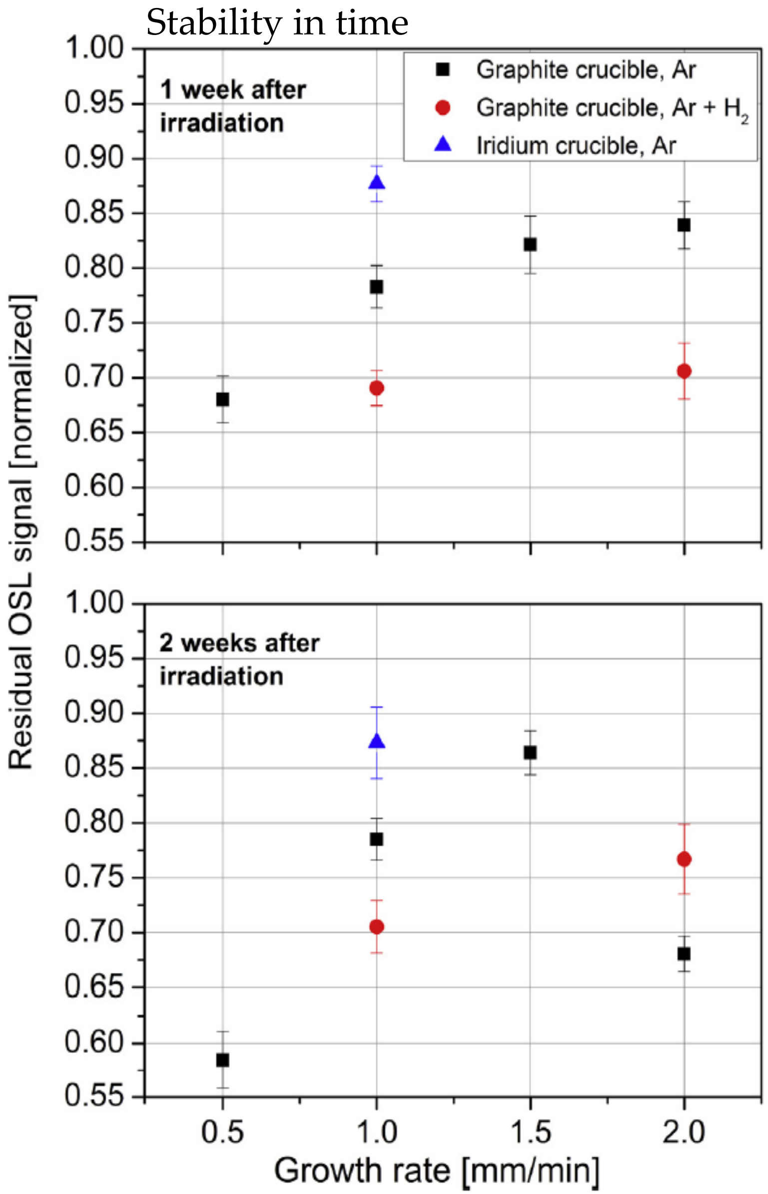
Results

Luminescence emission vs. growth parameters

- LiMgPO$_4$ (LMP) compound
- Grown with MPD method
- Growth rates[mm/min]:
  - 0.5
  - 1.0
  - 1.5
  - 2.0
- Crucible material:
  - Graphite
  - Iridium
- Atmosphere:
  - Ar
  - Ar+H$_2$





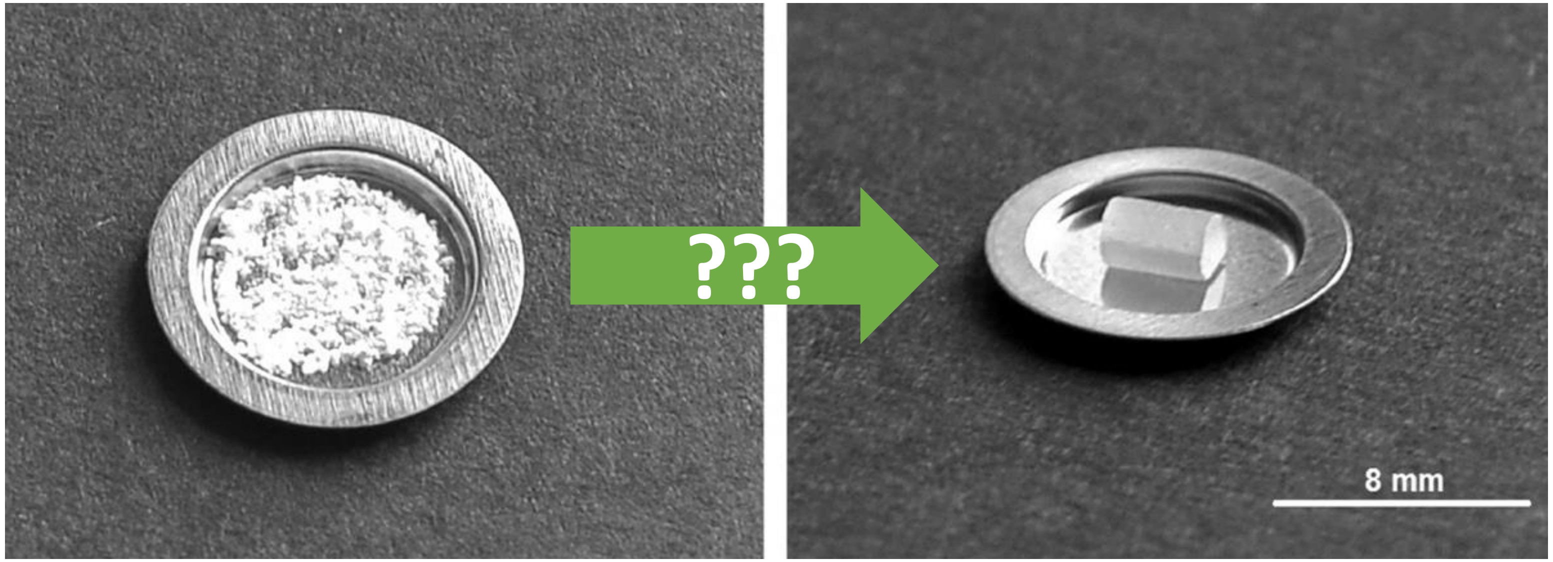


D. Kulig, **W. Gieszczyk**, P. Bilski, B. Marczewska, M. Kłosowski. Radiat. Meas. 90 (2016) 303 – 307

Results

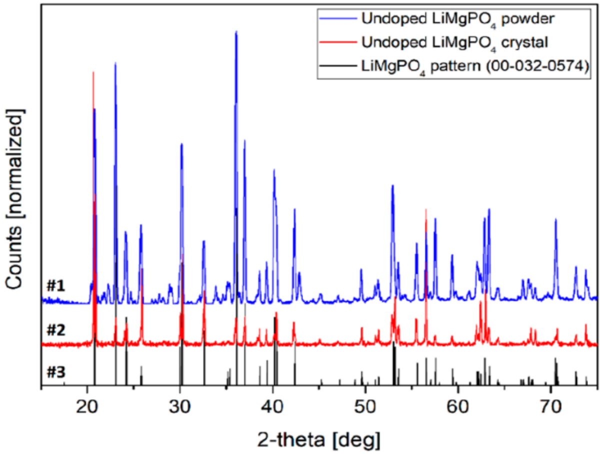
Powders vs. crystals

Do we really need crystals?



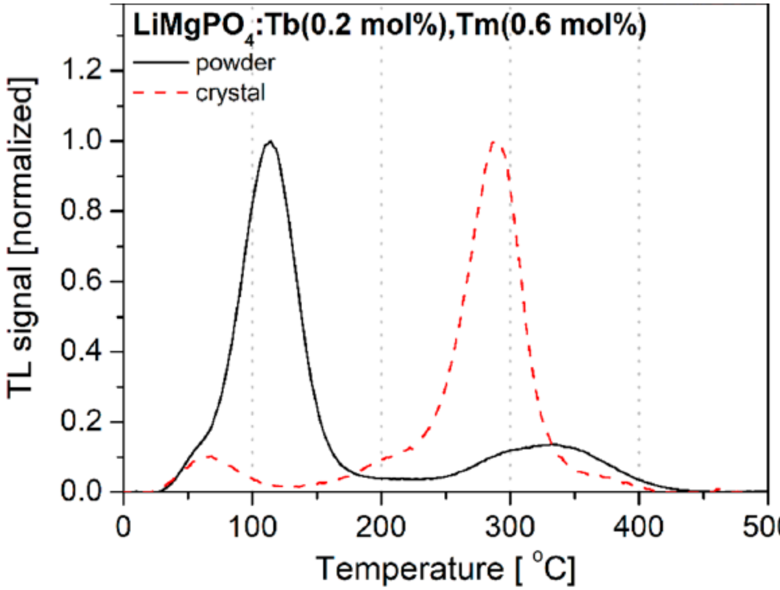
In general, we observed:

- Powders a little bit more sensitive to radiation
- Crystals exhibit lower fading
- Similar dose-response characteristics
- …



Advantages of using crystals:

- It is easier to operate with crystals …



- High-temperature growth changes the distribution of TL-related structure defects what is manifested in the changes of the shape of the measured glow-curves
- The effect is repeatable
- May strongly influence the fading properties

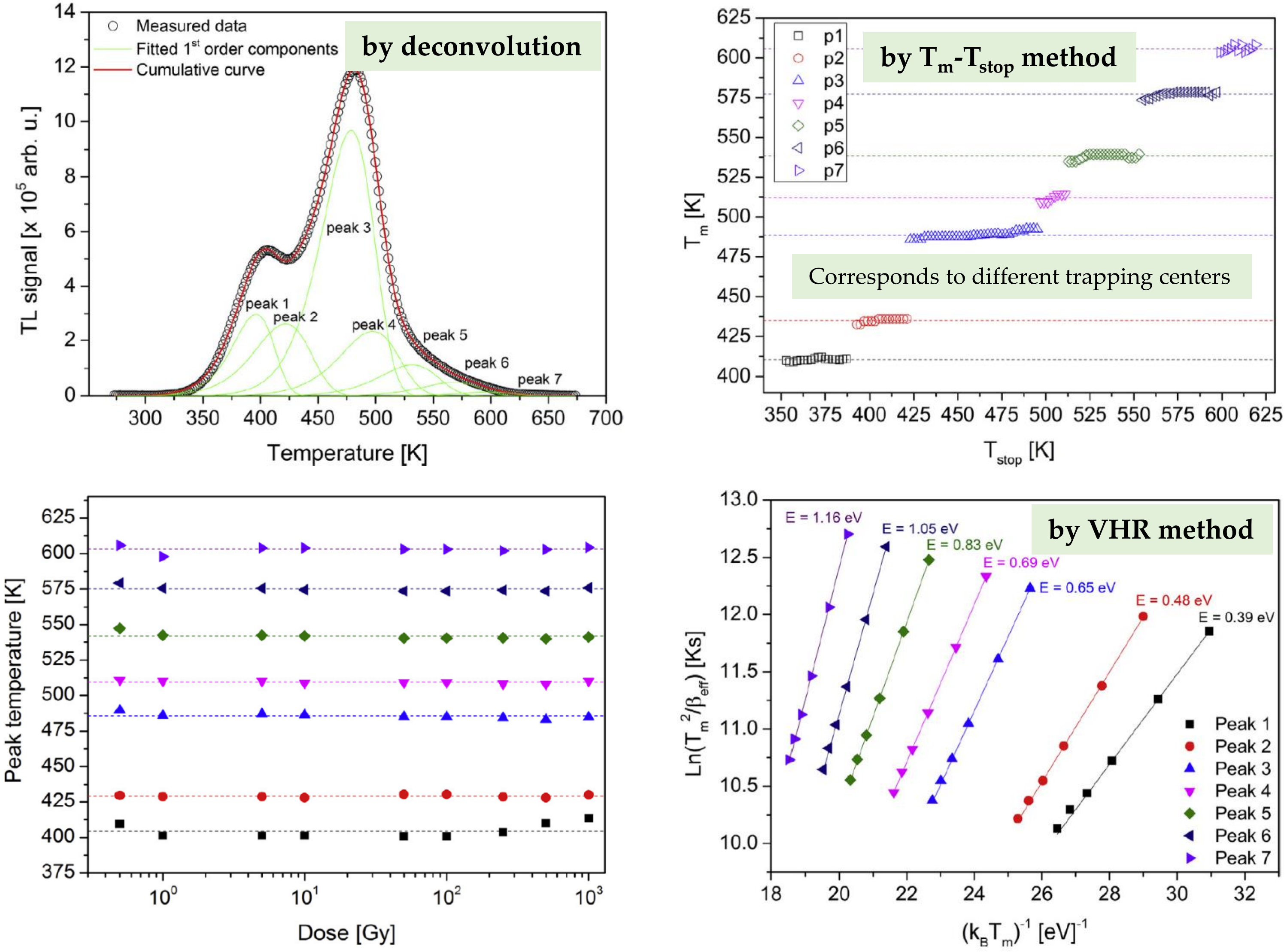
D. Kulig, **W. Gieszczyk**, B. Marczewska, P. Bilski, M. Kłosowski, A.L.M.C. Malthez. Radiat. Meas. 106 (2017) 94 – 99

Results

Trapping parameters evaluation

- Free charge carriers can be trapped by trapping centers related to the defect sites
- Each trapping center is characterized by several different trapping parameters like e.g. I_m, T_m, E (in TL); τ, σ (in OSL)
- Knowing the values of trapping parameters we can expect a specific behavior regarding e.g. the response to increasing radiation dose or stability of luminescence in time
- Trapping parameters evaluated using different methods (deconvolution, T_m-T_{stop}, VHR)

- Individual TL components separated from the measured glow-curves
- All the components were stable for increasing dose of radiation
- Dose-response was checked for each TL component
- Activation energy evaluated with VHR method



W. Gieszczyk, D. Kulig, P. Bilski, B. Marczewska, M. Kłosowski. Radiat. Meas. 106 (2017) 100 – 106

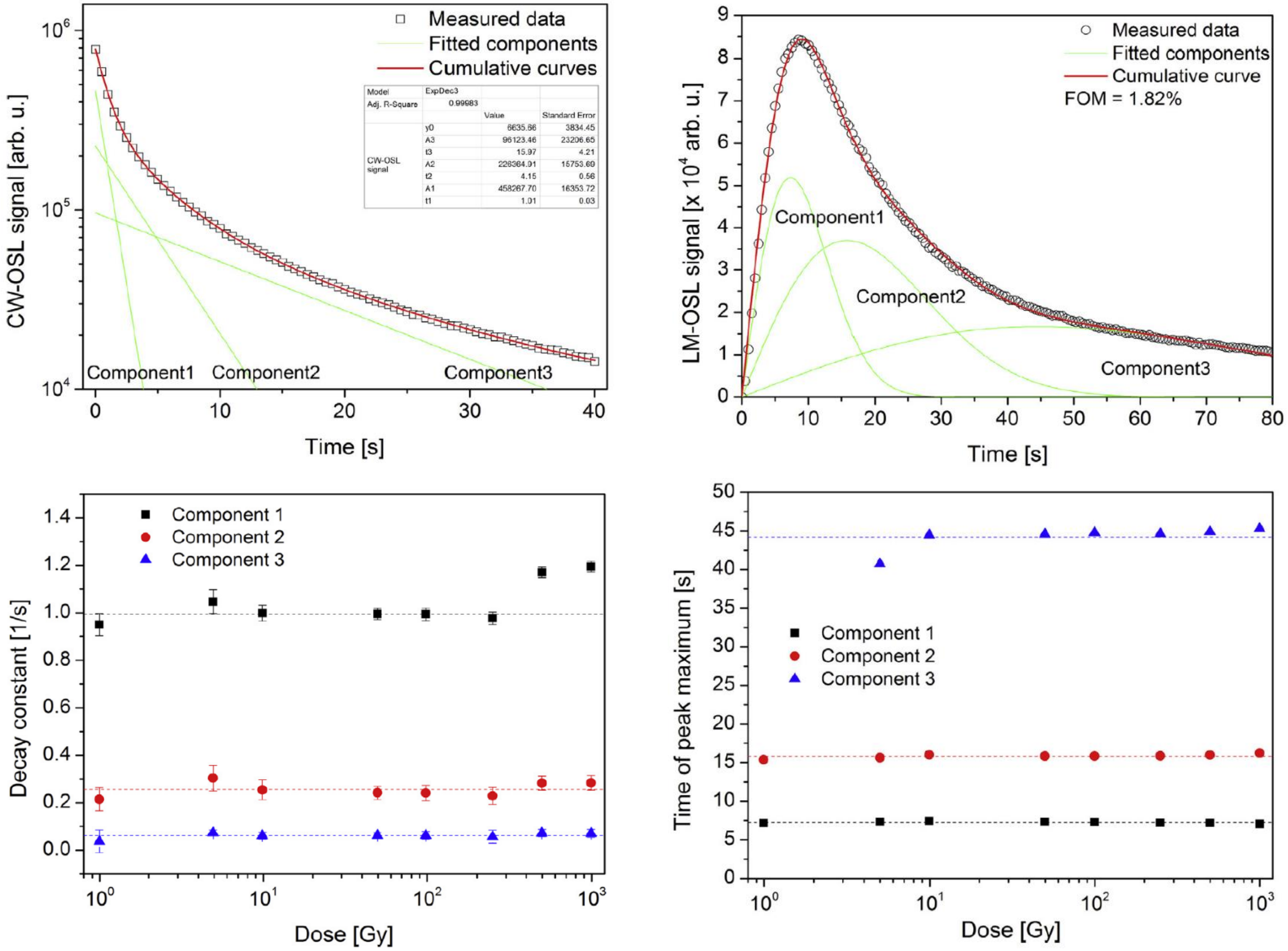
Results

Trapping parameters evaluation

Exemplary results (OSL):

- The undoped LMP crystal
- CW- and LM-OSL curves analyzed

- Both TL and OSL emission does not follow the first order kinetics directly, but can be easily expressed as a linear combination of several first order components.
- We can expect:
  - Stability for increasing dose
  - No retrapping
  - High fading because of low E



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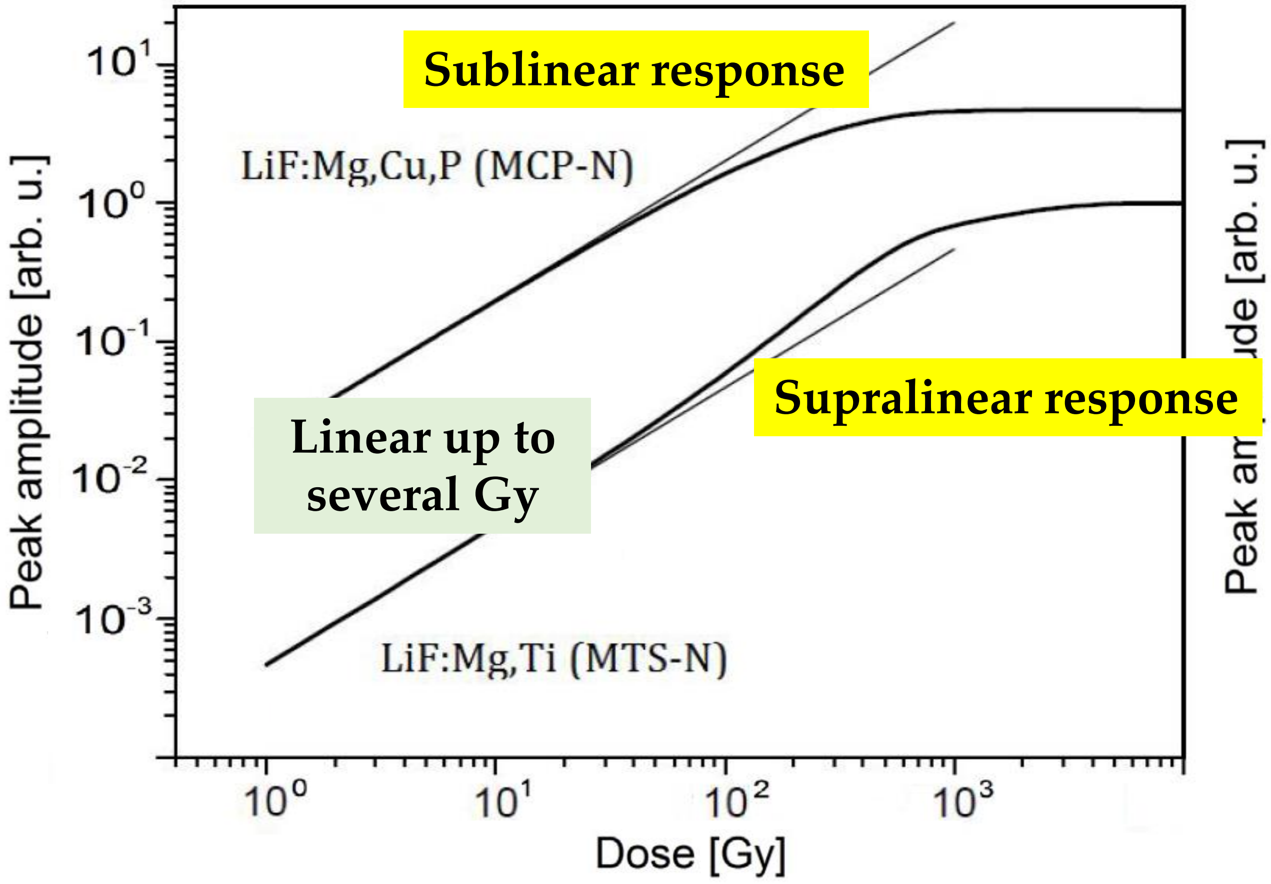
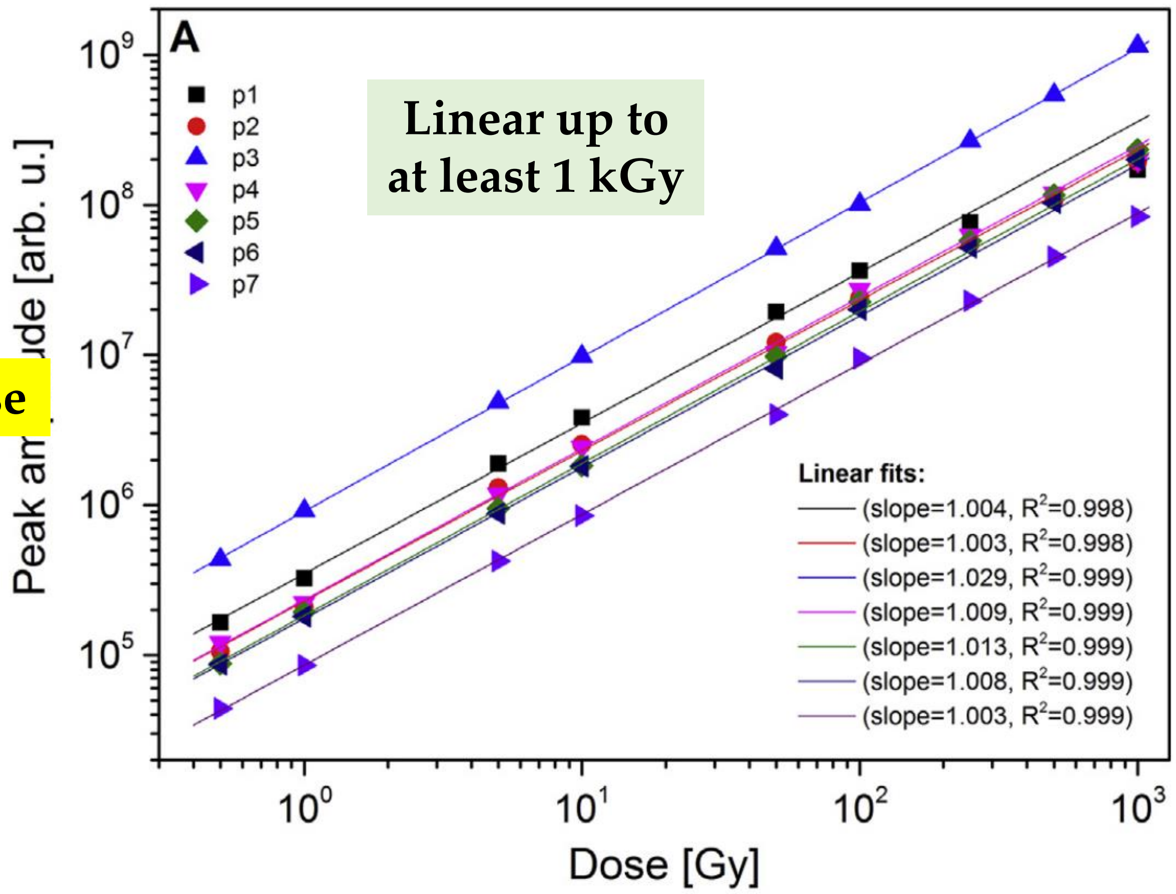
Results

Dose-response characteristics



Perfect linear response



Important for high-dose measurements (e.g. hadron therapy)

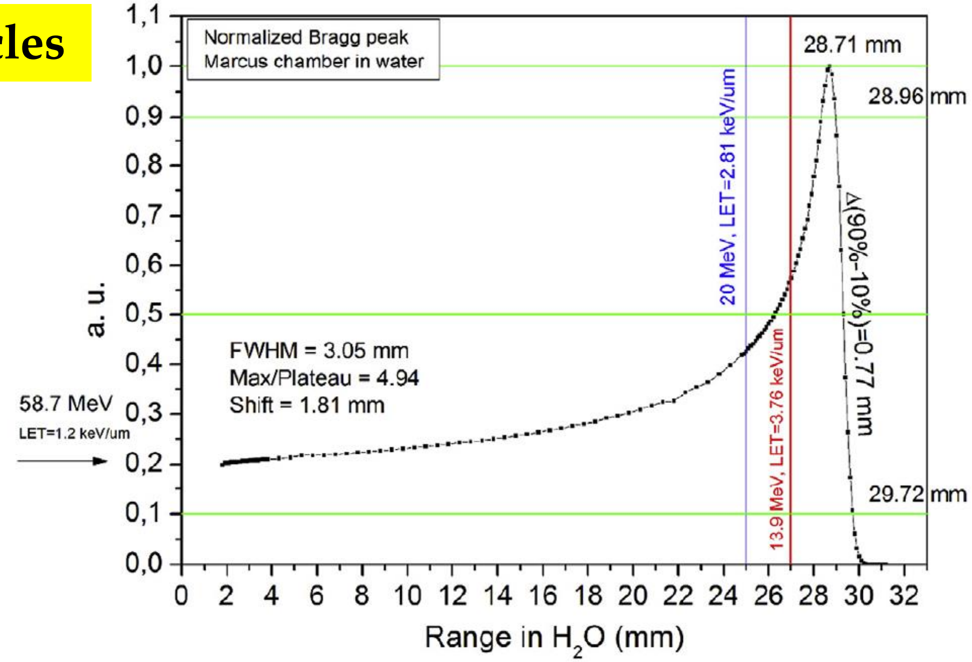
W. Gieszczyk, D. Kulig, P. Bilski, B. Marczewska, M. Kłosowski. Radiat. Meas. 106 (2017) 100 – 106

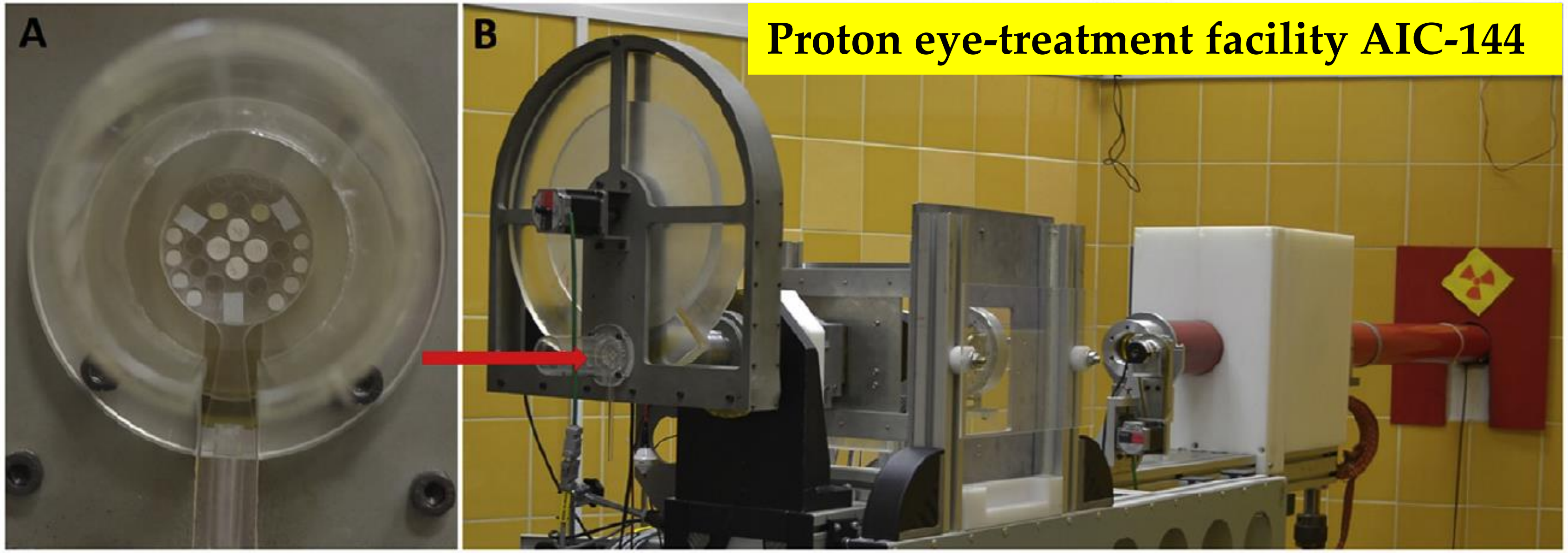
Results

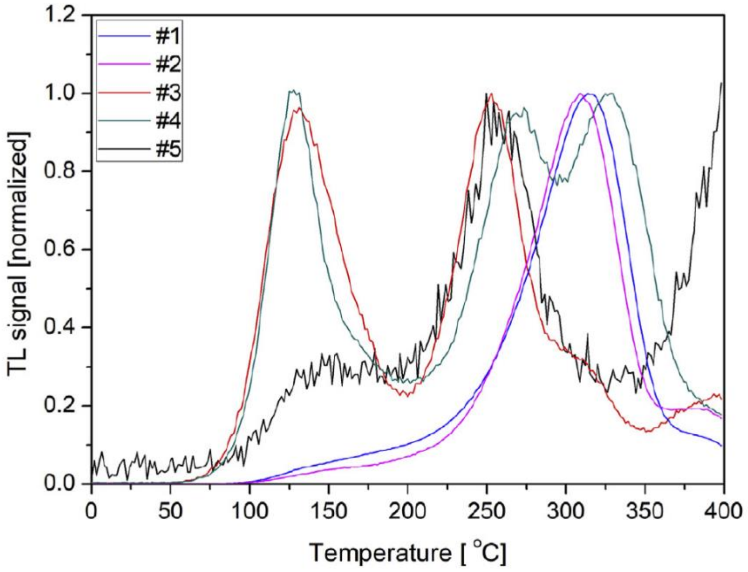
Response to charged particles

Samples under study

Sample ID	Raw material	Dopants concentration (%mol)						Sensitivity vs. LiF:Mg,Ti
		Tb	B	Eu	Er	Tm	Y	
#1	$LiMgPO_4$	–	10	–	–	0.8	–	2.78
#2		0.2	10	–	–	0.6	–	0.56
#3		0.4	10	–	0.4	–	–	0.05
#4		0.2	10	–	–	–	0.6	0.05
#5		0.4	10	0.4	–	–	–	$<$ 0.01
Reference	LiF:Mg,Ti, MTS-N	–	–	–	–	–	–	1.0





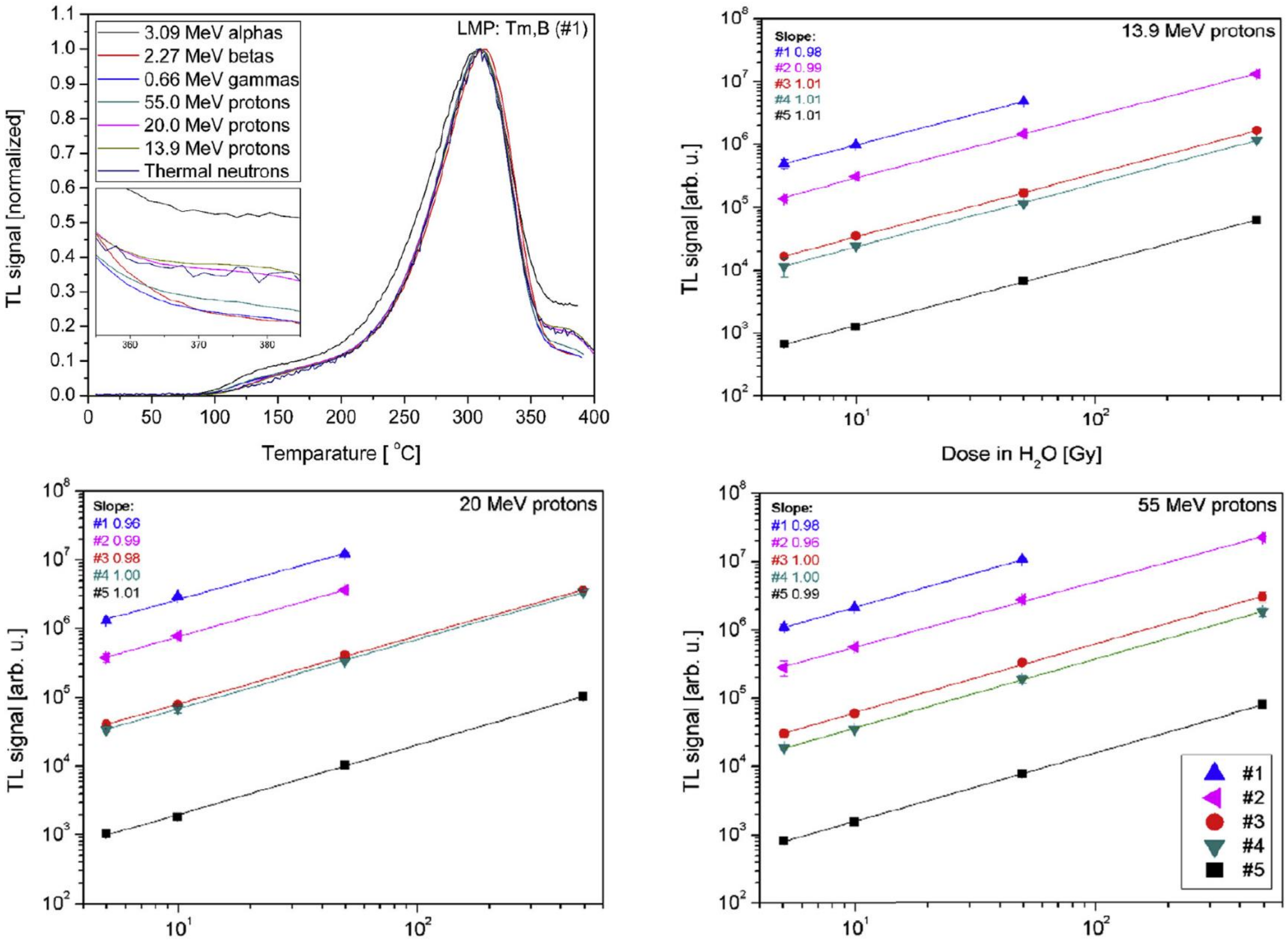


W. Gieszczyk, P. Bilski, M. Kłosowski, T. Nowak, L. Malinowski,. Radiat. Meas. 113 (2018) 14 – 19

Response to charged particles

Practically the same shape of glow-curves regardless the radiation type

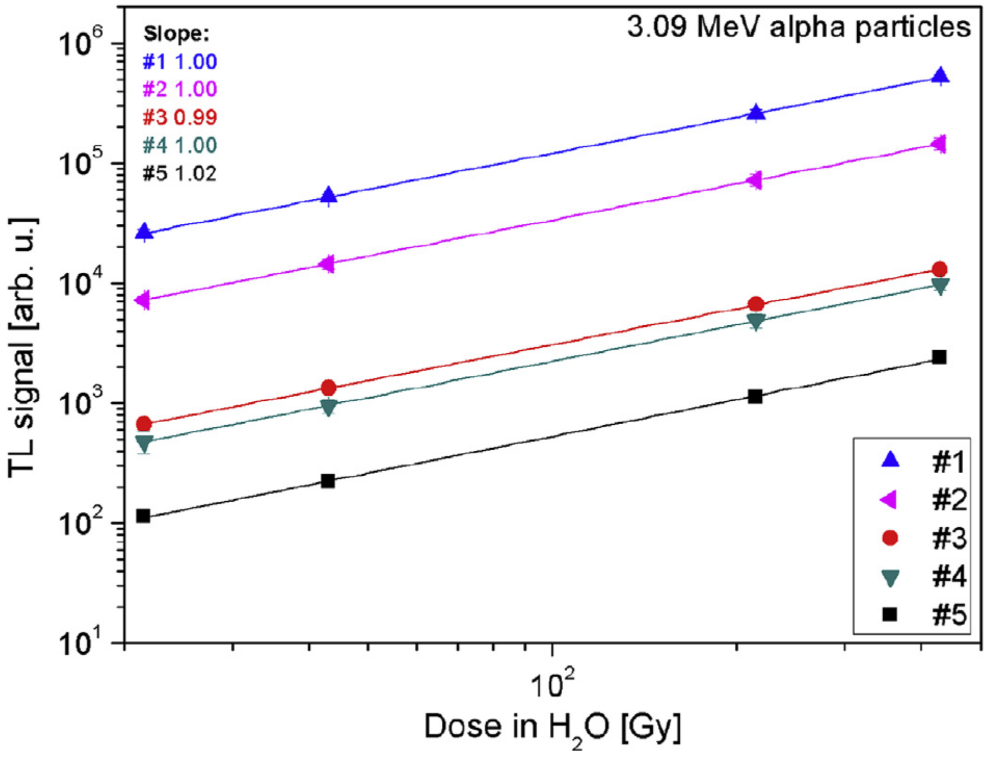
Perfect linear response regardless the proton beam energy

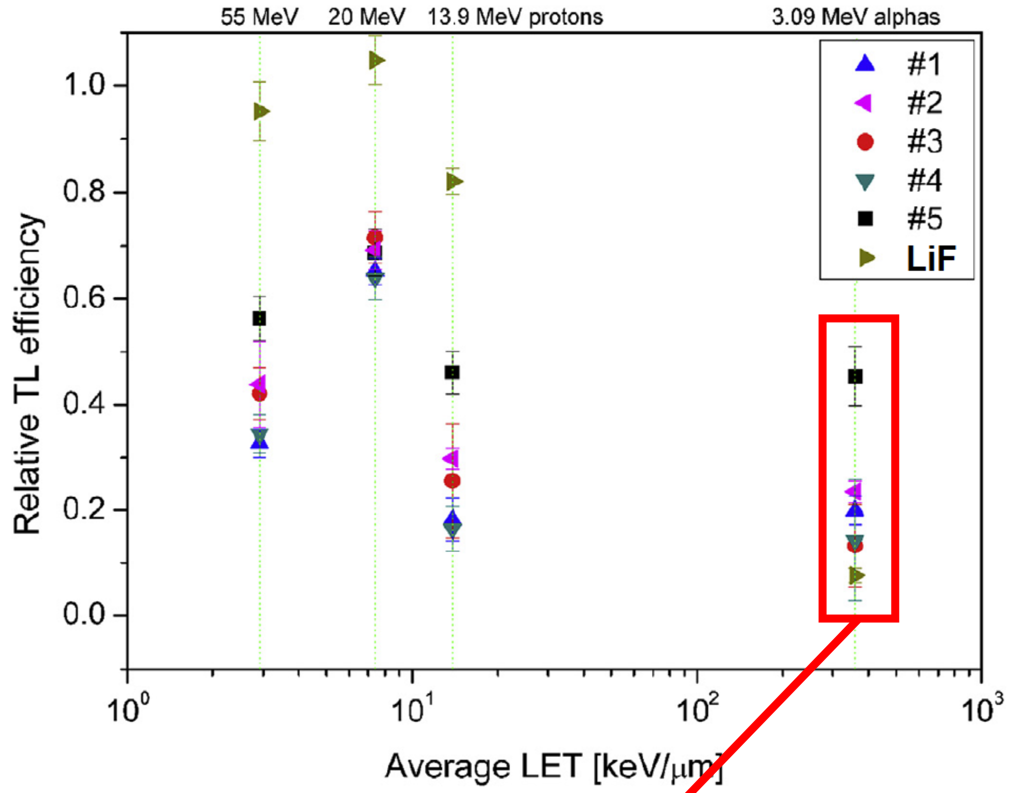


W. Gieszczyk, P. Bilski, M. Kłosowski, T. Nowak, L. Malinowski,. Radiat. Meas. 113 (2018) 14 – 19

Response to charged particles – influence of ionization density

For α-particles the response is also perfectly linear





$$\eta_{rel} = \frac{\eta_i}{\eta_{ref}} = \frac{TL_i}{D_i \cdot m_i} \cdot \frac{D_{ref} \cdot m_{ref}}{TL_{ref}}$$

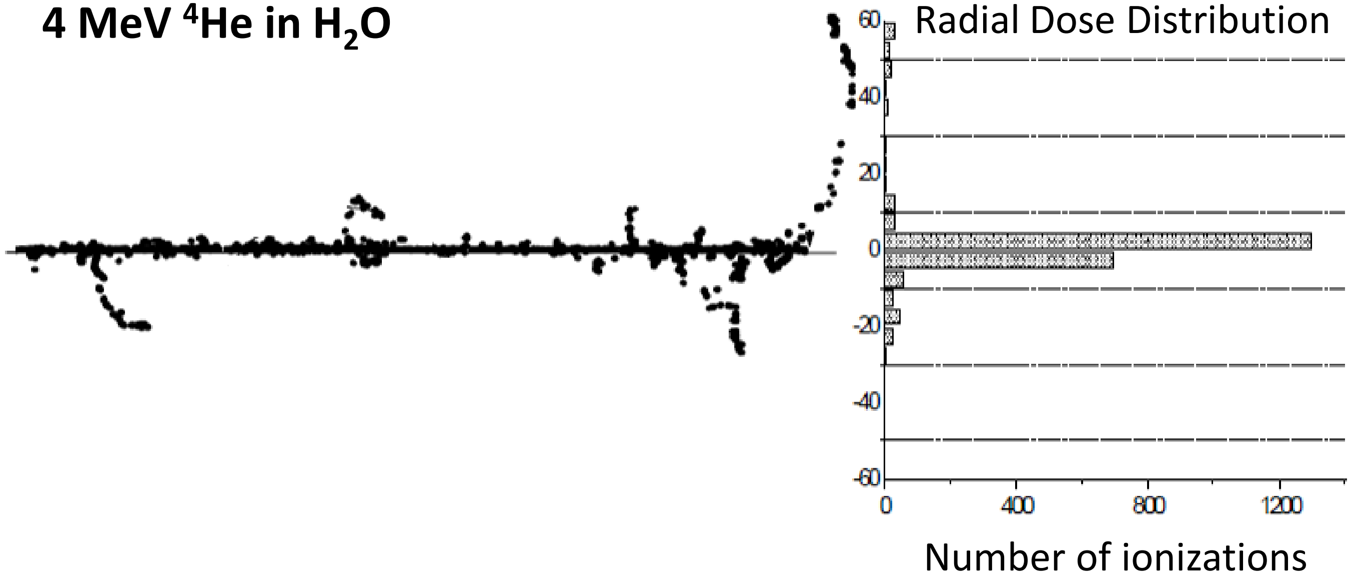
Even the LMP crystal of lowest efficiency shows a higher response to alpha particles than the reference LiF:Mg,Ti sample

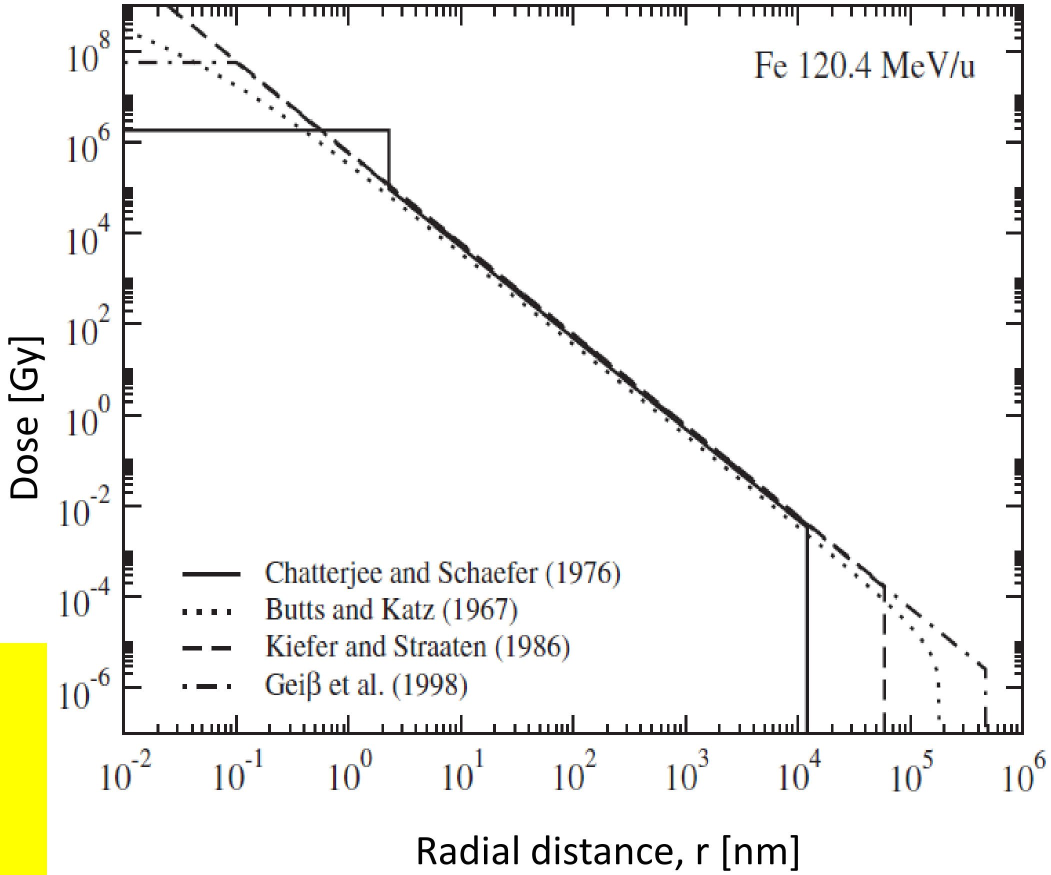
W. Gieszczyk, P. Bilski, M. Kłosowski, T. Nowak, L. Malinowski,. Radiat. Meas. 113 (2018) 14 – 19

Response to charged particles

Probable explanation

4 MeV ^4He in H_2O





- Several models of RDD exist
- Predicted dose within track core ~ 10^6 Gy
- No experimental verification
- Lack of detectors of appropriate spatial resolution
- LiF detectors response saturates typically at around 10^3 Gy, but …

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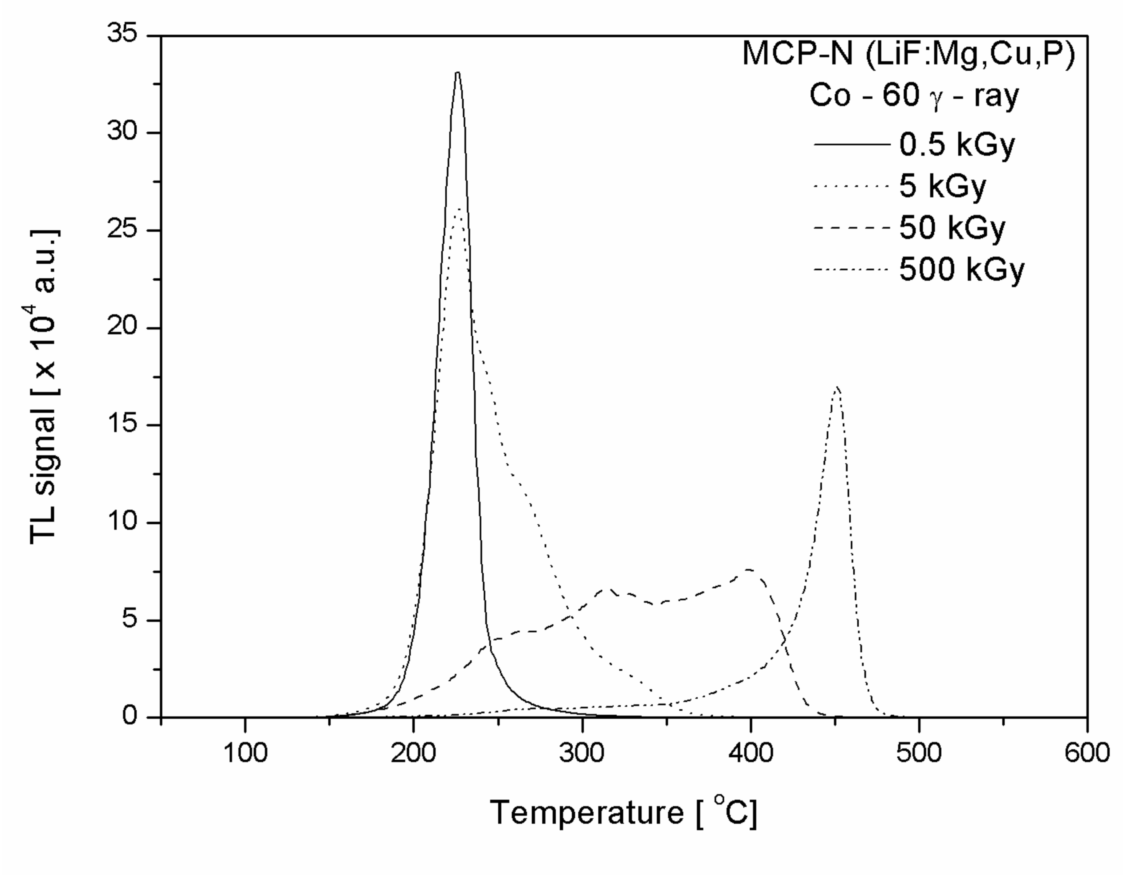
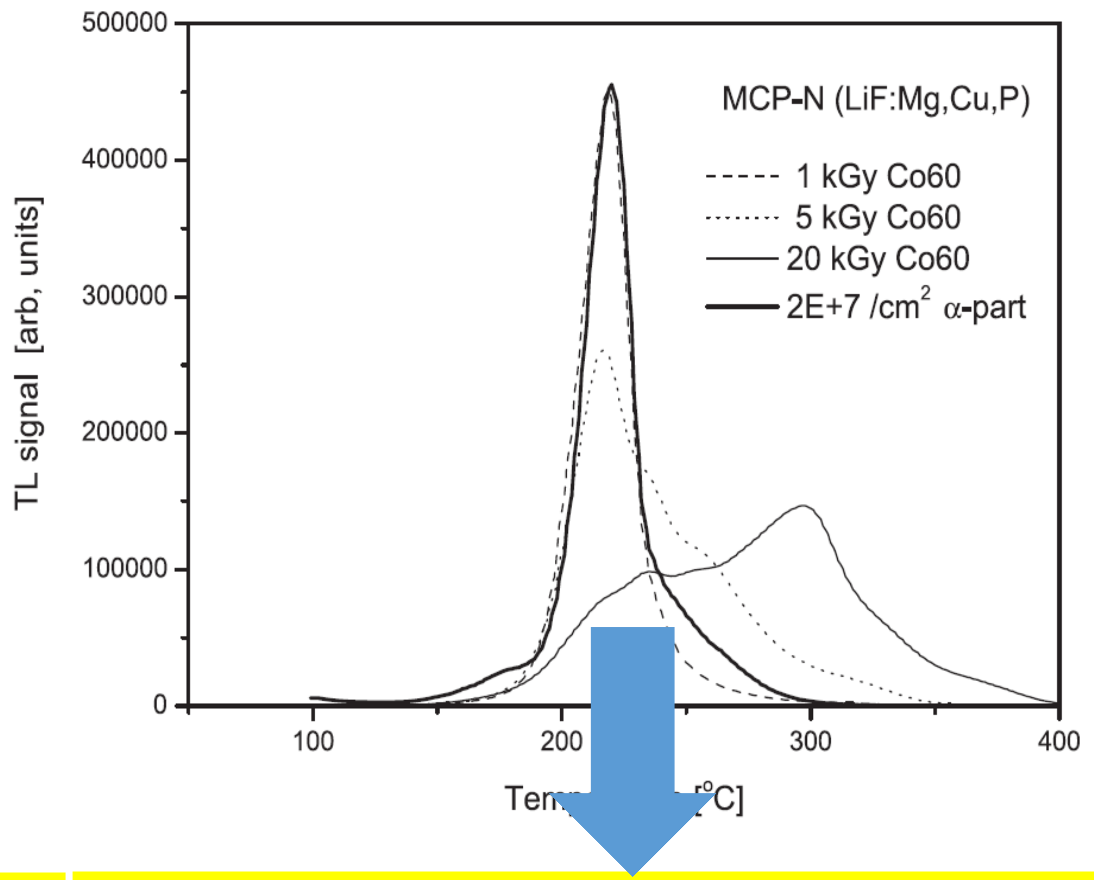
Response to charged particles

… a high-temperature structure of LiF:Mg,Cu,P (MCP) glow-curve has been discovered





LiF main peak response is far saturated at this dose level while for the LMP no saturation observed at least to 10 kGy!!!

Around 20% of the entire energy of alpha particle is deposited with local doses > 50kGy

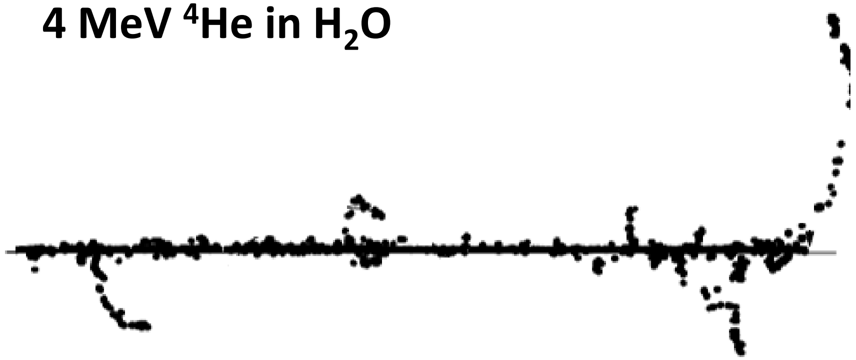
P. Olko, P. Bilski, **W. Gieszczyk**, L. Grzanka, B. Obryk. Radiat. Meas. 46 (2011) 1349 - 1352

Results

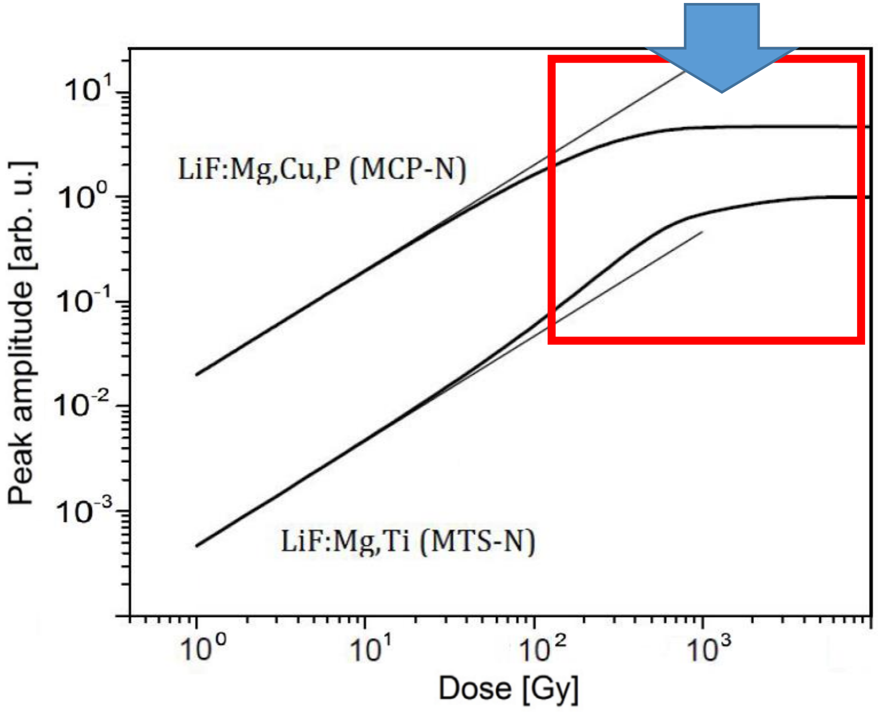
Response to charged particles

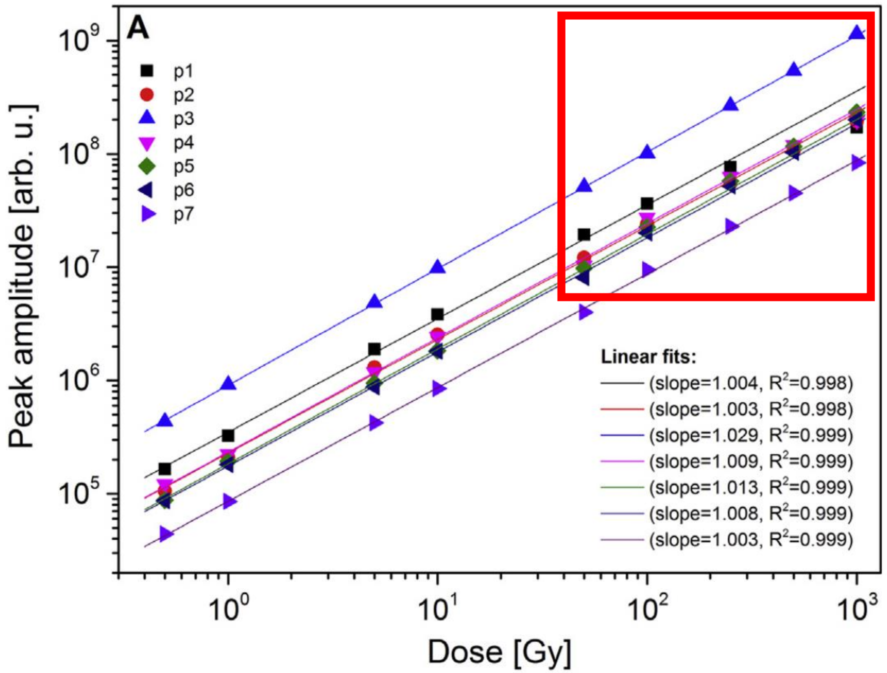
Around 20% of the entire energy of alpha particle is deposited with local doses > 50kGy

4 MeV ^{4}He in H_2O



Response saturated = efficiency decreased





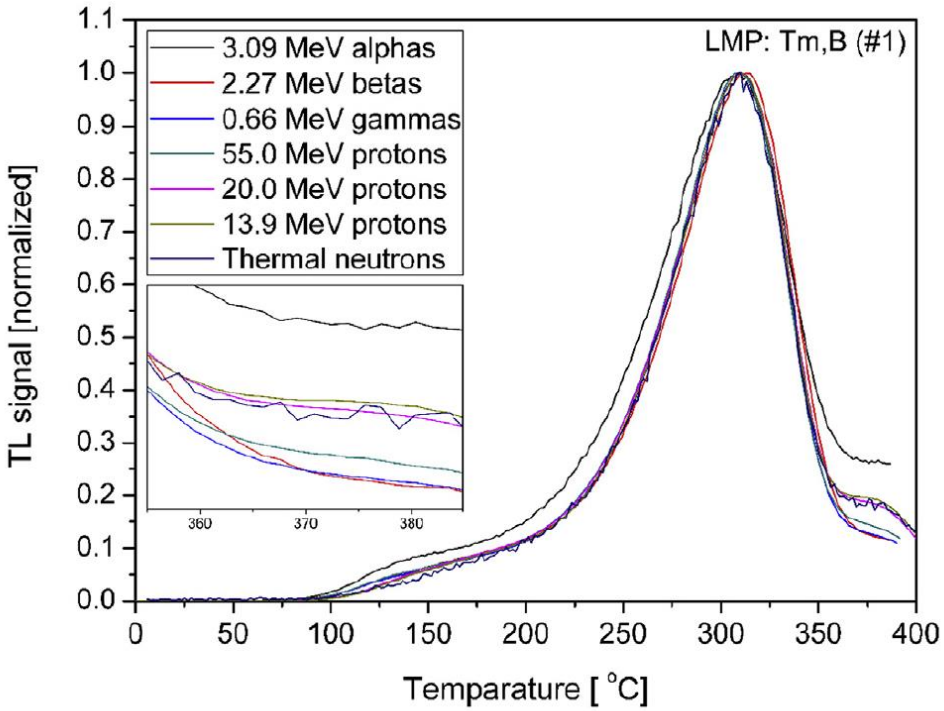
Linear response = efficiency not decreased

P. Olko, P. Bilski, **W. Gieszczyk**, L. Grzanka, B. Obryk. Radiat. Meas. 46 (2011) 1349 - 1352

Response to thermal neutrons

Results for differently doped LMP crystals

- ^{239}Pu/Be source moderated with 10 cm polyethylene;
- Neutron fluence rate: $1.42 \cdot 10^4$ n/h·cm^2 (evaluated with ^{6}LiF:Mg,Ti calibrated at PTB Geesthacht Neutron Facility);
- Gamma-ray background: 5.9 μGy/h (measured with ^{7}LiF:Mg,Cu,P);
- Gamma dose subtracted from the total response of LMP crystals;
- Irradiation time: 5d 18h 10 m (corresponds to the fluence of $1.96 \cdot 10^6$ n/cm^2)
- Data corrected for the fading factor evaluated for the Co-60 gamma rays for the same irradiation time
- Samples were shielded from a daylight during the irradiation and transportation



Sample ID	Raw material	Dopants concentration (%mol)						Sensitivity[a]	Response to thermal	Relative TL efficiency[b]			
		Tb	B	Eu	Er	Tm	Y	vs. LiF:Mg,Ti	neutrons [mGycm^2/n][b]	55 MeV p	20 MeV p	13.9 MeV p	3.09 MeV α
#1	LiMgPO$_4$	–	10	–	–	0.8	–	2.78	$3.82 \cdot 10^{-6}$	0.33 ± 0.03	0.65 ± 0.02	0.18 ± 0.04	0.20 ± 0.03
#2		0.2	10	–	–	0.6	–	0.56	$3.52 \cdot 10^{-6}$	0.44 ± 0.08	0.69 ± 0.03	0.30 ± 0.02	0.23 ± 0.02
#3		0.4	10	–	0.4	–	–	0.05	$4.19 \cdot 10^{-6}$	0.42 ± 0.05	0.71 ± 0.05	0.26 ± 0.05	0.13 ± 0.03
#4		0.2	10	–	–	–	0.6	0.05	$5.11 \cdot 10^{-6}$	0.34 ± 0.03	0.64 ± 0.04	0.16 ± 0.03	0.14 ± 0.02
#5		0.4	10	0.4	–	–	–	< 0.01	–	0.56 ± 0.04	0.69 ± 0.04	0.46 ± 0.04	0.45 ± 0.05
Reference	LiF:Mg,Ti, MTS-N	–	–	–	–	–	–	1.0	$3.50 \cdot 10^{-6}$	0.95 ± 0.05	1.05 ± 0.05	0.82 ± 0.02	0.08 ± 0.01

W. Gieszczyk, P. Bilski, M. Kłosowski, T. Nowak, L. Malinowski,. Radiat. Meas. 113 (2018) 14 – 19

Response to thermal neutrons

The response of LMP to thermal neutrons is similar to the response of LiF

In both cases, the only element active to neutrons is Li

	LiF	$LiMgPO_4$
Molar ratio	**1:1**	**1:6**

Response to thermal neutrons $[mGycm^2/n]$[b]	
$3.82 \cdot 10^{-6}$	LMP
$3.52 \cdot 10^{-6}$	
$4.19 \cdot 10^{-6}$	
$5.11 \cdot 10^{-6}$	
–	
$3.50 \cdot 10^{-6}$	LiF

- The content of Li in LiF is much higher than in $LiMgPO_4$
- The main product of the interaction of neutrons with Li is alpha particle $Li(n,\alpha)^3H$
- Response of LMP to alpha particles is higher than the response of LiF
- These two effects compensate each other resulting in a similar efficiency to thermal neutrons

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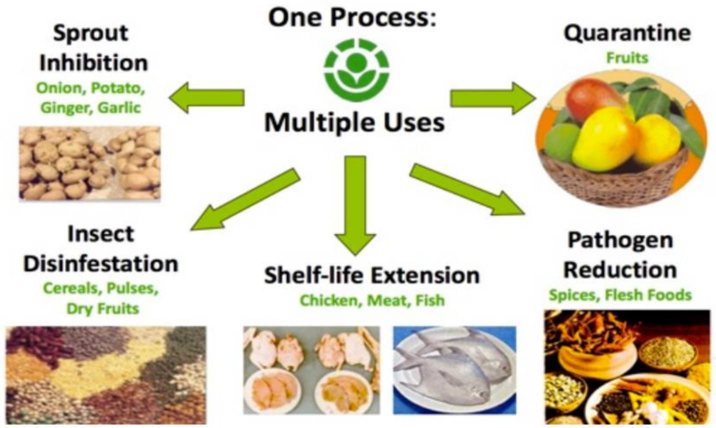
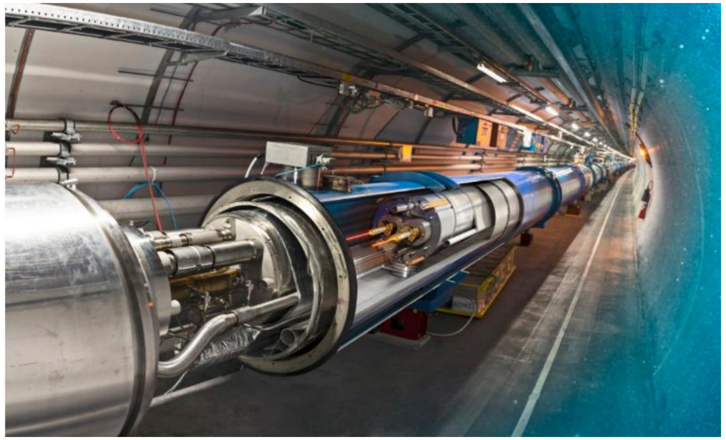
Results

Novel applications



- High-dose dosimetry, kGy range (food preservation, sterilization)

- Dosimetry of charged particles (hadron therapy)
- Dosimetry of neutrons (monitoring of areas around particle accelerators)



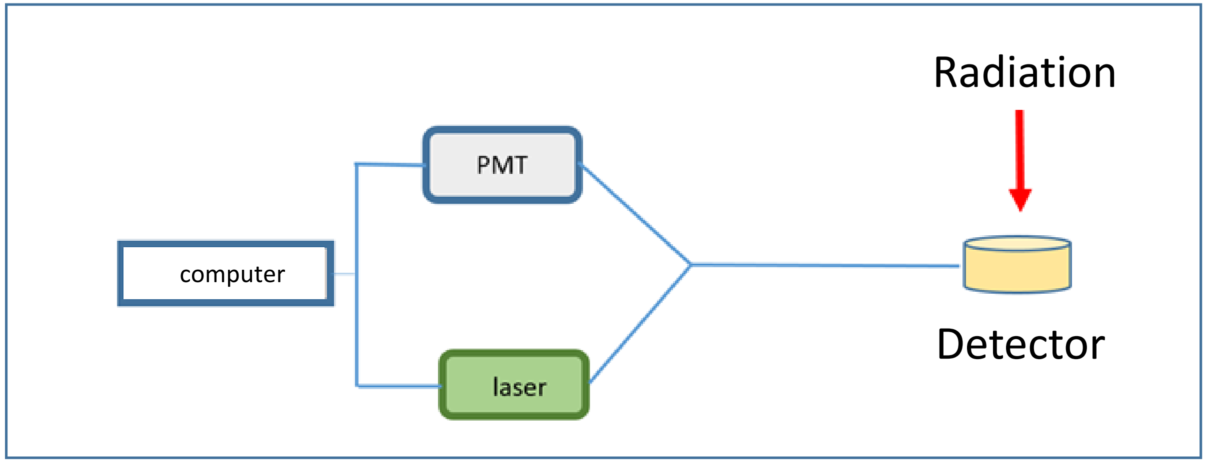
- Real-time measurements of therapeutic proton beam (prof. B. Marczewska)
- 2D/3D OSL dosimetric system based on LMP foils (dr. M. Sądel)

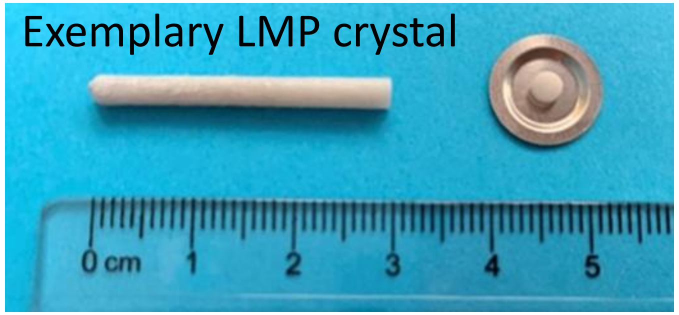
Novel applications

Real-time measurements of therapeutic proton beam
(National Science Center, OPUS program – P.M. prof. Barbara Marczewska)

Concept:

- Small detector (crystal) placed at the end of optical fiber
- The optical fiber can be even several dozen meters long
- The optical fiber connects the crystal to the apparatus for stimulation and signal registration
- Different modes of measurements are possible
  - Simultaneous or sequential registration of RL and OSL signal
  - Constant or pulsed stimulation



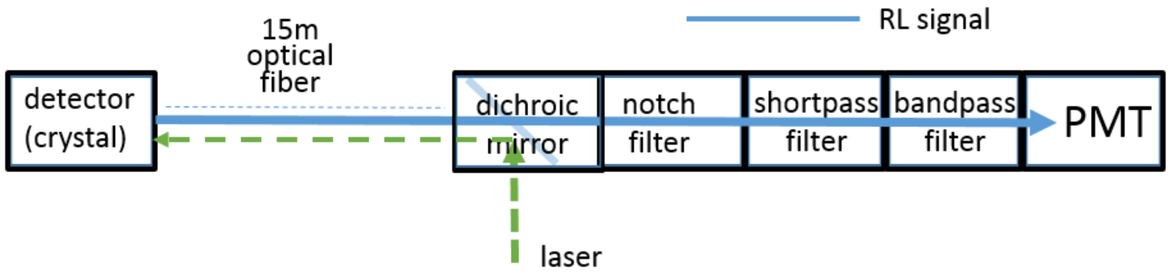


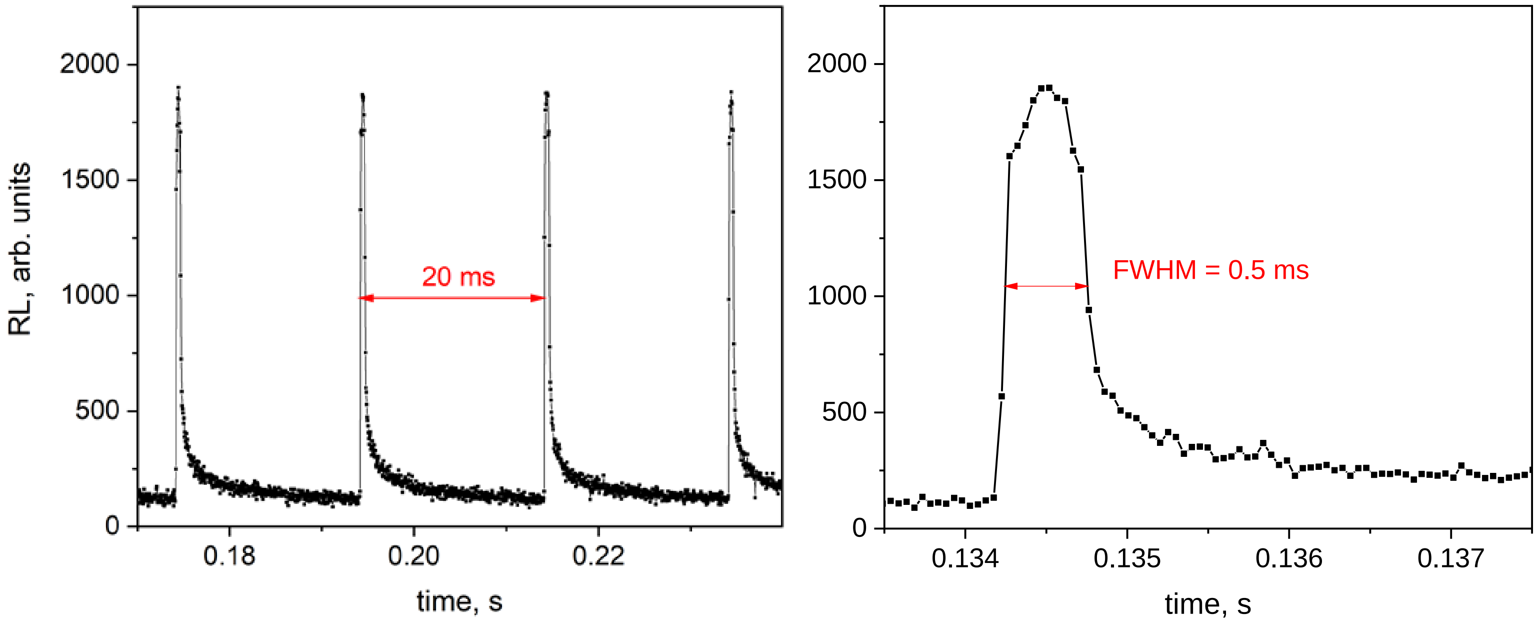
Detector:
- Sample of the volume of 1-3mm^3 (spatial resolution)
- $LiMgPO_4$ crystals
- *in-vivo, in-situ, in real-time*

A. Sas-Bieniarz, B. Marczewska , P. Bilski, **W. Gieszczyk**, M. Kłosowski. Radiat. Meas. 136 (2020), 106408

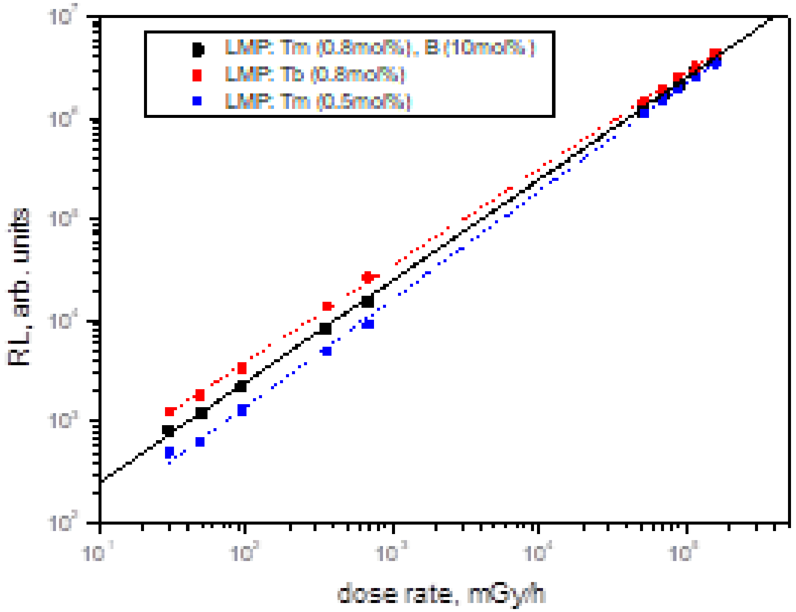
Novel applications

Real-time measurements of therapeutic proton beam
(National Science Center, OPUS program – P.M. prof. Barbara Marczewska)





Measurements of time-structure of proton beam from AIC-144 cyclotron



Dose-rate effect on the LMP RL emission measured over a broad range of dose-rates (performed with Cs-137 and Co-60 sources)

A. Sas-Bieniarz, B. Marczewska , P. Bilski, **W. Gieszczyk**, M. Kłosowski. Radiat. Meas. 136 (2020), 106408

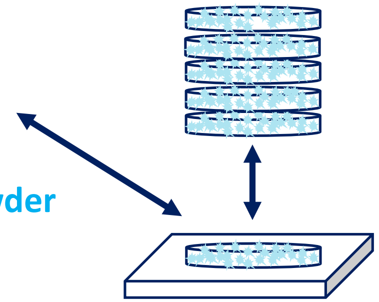
Novel applications

2D OSL dosimetric system based on $LiMgPO_4$ silicone foils
(Foundation for Polish Science, Homing Program – P.M. dr. Michał Sądel)

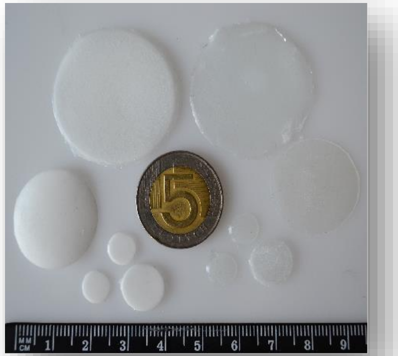
Prototype foils preparation

Silicone

LMP powder



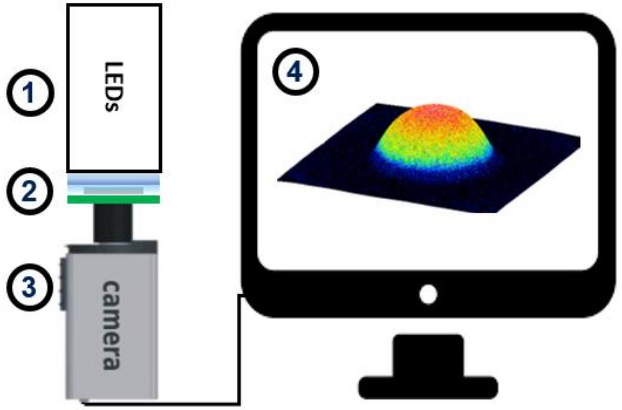
2D LMP foils



2D foils placed on the hand phantom

- ✓Thickness: ~0.5 mm
- ✓Foils size: up to ø25 mm
- ✓Waterproof
- ✓Hyperelastic
- ✓No denisity changes

Optical imaging system



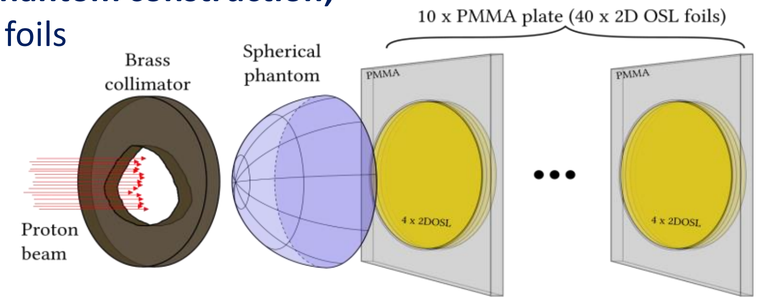
1. LED source (470 nm)
2. Filters set
3. High-sensitive CCD camera
4. Fast 2D/3D data acquisition

Novel applications

2D OSL dosimetric system based on $LiMgPO_4$ silicone foils
(Foundation for Polish Science, Homing Program – P.M. dr. Michał Sądel)

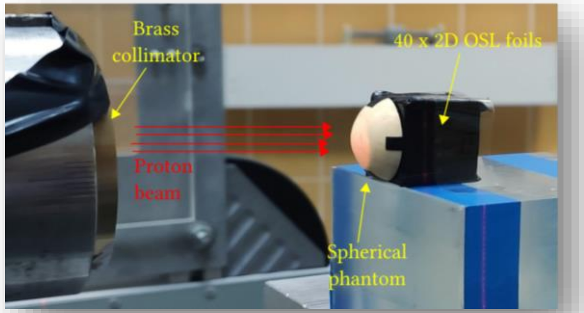
Verification of a real 3D eye-ball clinical treatment plan

Eyeball phantom construction;
- 40 LMP foils

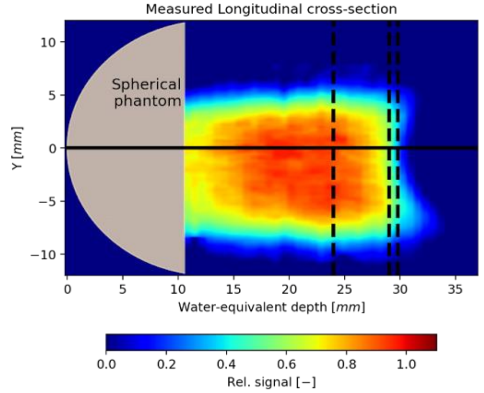


Experimental setup

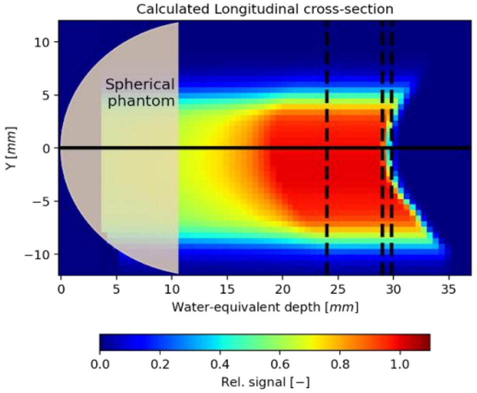
Proton beam;
- Protons: **60 MeV**
- Range: **29 mm**
- Modulation: **10 mm**



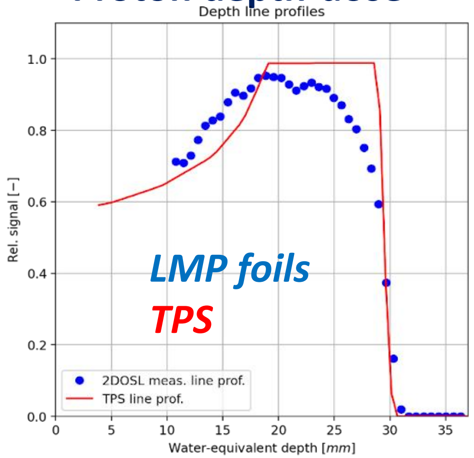
Measured (40 LMP)



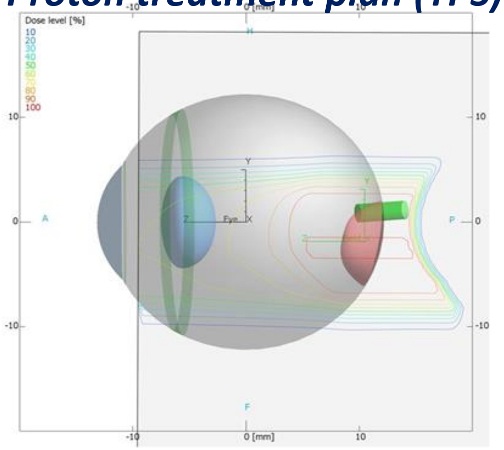
Calculated (TPS)



Proton depth-dose



Proton treatment plan (TPS)



Conclusions

New high-sensitive luminescent material has been developed and optimized

- Since 2014, more than 100 different compositions of $LiMgPO_4$:RE compound were investigated
- TL, OSL, RL, CL emissions have been studied for differently doped crystals
- Y, Sm, Eu, Gd, Tb, Er, Tm, Yb were investigated as possible dopants influencing efficiency of LMP crystals

LMP sensitivity comparable or higher than LiF (in TL) and Al_2O_3 (in OSL)

Investigations performed within this work

- Growth conditions have been optimized and their influence on crystal sensitivity has been checked
- Comparison between powders and crystals was performed showing a superiority of crystals
- Trapping parameters have been evaluated for selected LMP crystals
- Basic luminescence and dosimetric properties were studied:
  - Sensitivity to ionizing radiation against LiF detectors
  - Dose-response characteristics
  - Response to charged particles
  - Response to thermal neutrons

LMP crystal growth parameters optimized (crystals better than powders)

Tb dopant is best for OSL measurements
Tm dopant is best for TL and RL measurements

Eu-doped crystal showed highest relative efficiency for alpha-particles → best for HCP measurements

All investigated compositions showed linear response up to at least 1 kGy

Novel applications presented

- Applications to real-time measurements and 2D dose distribution assessment

General comment

- The obtained results clearly indicate that the LMP compound may be considered as promising material for dosimetric application

Published papers on LMP

D. Kulig (Wróbel), **W. Gieszczyk**⊠, P. Bilski, B. Marczewska, M. Kłosowski.
Thermoluminescence and optically stimulated luminescence studies on $LiMgPO_4$ *crystallized by micro pulling down technique.* **Radiation Measurements 85 (2016), 88-92**

D. Kulig (Wróbel), **W. Gieszczyk**⊠, P. Bilski, B. Marczewska, M. Kłosowski.
New OSL detectors based on $LiMgPO_4$ *crystals grown by micro pulling down method. Dosimetric properties vs. growth parameters.* **Radiation Measurements 90 (2016), 303-307**

D. Kulig (Wróbel), **W. Gieszczyk**⊠, B. Marczewska, P. Bilski, M. Kłosowski, A.L.M.C. Malthez.
Comparative studies on OSL properties of $LiMgPO_4$*:Tb,B powders and crystals.* **Radiation Measurements 106 (2017), 94-99**

W. Gieszczyk⊠, D. Kulig (Wróbel), P. Bilski, B. Marczewska, M. Kłosowski.
Analysis of TL and OSL kinetics in lithium magnesium phosphate crystals. **Radiation Measurements 106 (2017), 100-106**

W. Gieszczyk⊠, P. Bilski, M. Kłosowski, T. Nowak, L. Malinowski.
Thermoluminescent response of differently doped lithium magnesium phosphate ($LiMgPO_4$*, LMP) crystals to protons, neutrons and alpha particles.* **Radiation Measurements 113 (2018), 14-19**

A.L.M.C. Malthez, B, Marczewska, D. Kulig, P. Bilski, M. Kłosowski.
Optical and thermal pre-readout treatments to reduce the influence of fading on LiMgPO4 OSL measurements. **Applied Radiation and Isotopes 136 (2018), 118–120**

W. Gieszczyk⊠ , B. Marczewska, M. Kłosowski, A. Mrozik, P. Bilski, A. Sas-Bieniarz, P. Goj, P. Stoch.
Thermoluminescence enhancement of $LiMgPO_4$ *crystal host by* Tb^{3+} *and* Tm^{3+} *trivalent rare-earth ions co-doping.* **Materials 12 (2019), 2861**

B. Marczewska⊠, A. Sas-Bieniarz, P. Bilski, **W. Gieszczyk**, M. Kłosowski, M. Sądel.
OSL and RL of $LiMgPO_4$ *crystals doped with rare earth elements.* **Radiation Measurements 129 (2019), 106205**

A. Sas-Bieniarz, B. Marczewska⊠, P. Bilski, **W. Gieszczyk**, M. Kłosowski.
Study of radioluminescence in $LiMgPO_4$ *doped with Tb, B and Tm.* **Radiation Measurements 136 (2020), 106408**

A. Sas-Bieniarz, B. Marczewska, M. Kłosowski, P. Bilski, **W. Gieszczyk⊠.**
TL, OSL and RL emission spectra of RE-doped $LiMgPO_4$ *crystals.* **Journal of Luminescence 218 (2020), 116839**

W. Gieszczyk⊠, P. Bilski, A. Mrozik, M. Kłosowski, B. Marczewska, A. Sas-Bieniarz, M. Perzanowski, T. Zorenko and Yu. Zorenko.
Intrinsic and dopant-related luminescence of undoped and Tb plus Tm double-doped lithium magnesium phosphate ($LiMgPO_4$*, LMP) crystals.* **Materials 13 (2020), 2032**

Marczewska⊠, B., **Gieszczyk, W.**, Kłosowski, M., Książek, M., Bilski, P., Boroń, Ł.
Uniformity of thermoluminescence and optically stimulated Luminescence signals over the length of doped $LiMgPO_4$ *crystal rods grown by micro-pulling-down method.* **Materials 14 (2021), 132**

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- Michał Sądel

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- Paweł Goj
- Paweł Stoch

To the polish institutions supporting our research

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Thank you very much for your attention!!! ☺