Progress in Fabrication of Long YAG-based Scintillation Fibers for HEP Experiments

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Requirements to scintillators

[1]

Physico-chemical properties

Structure / Space group	Cubic / Ia3d
Density (g/cm^3)	6.73
Zeff	62.9
Radiation length X_0 (cm)	1.41
Interaction length (cm)	23.3 *LuAP: 19.8* *Fe: 17*
Hardness (Mohs)	7.5 *PWO: 3* *BGO, glass: 5*
Fracture toughness (Mpa.m$^{1/2}$)	1.1
Cleavage plane / H_2O solubility	No / No
Melting point (°C)	2260
Thermal expansion @ RT (°K^{-1})	8.8 10^{-6}
Thermal conductivity @ RT (W/m°K)	31

Optical properties

Light yield: Ce or Pr doped (ph/MeV)	20'000 *1/2 NaI(Tl)*
d(LY)/dT	?
Emission wavelength (nm): Ce doped Pr doped	535 290, 350
Decay time (ns): Ce doped Pr doped	70 20
Refractive index @ 633nm (isotropic) n^2= 3.3275151 - 0.0149248 λ^2	1.842 *Quartz: 1.55*
Fundamental absorption undoped (nm)	250
Max. Cerenkov 1/2 angle	57°
Total reflexion 1/2 angle	33°
Cerenkov threshold e energy (KeV)	97

Long (>20 cm) crystalline fibers with good transparency (attenuation length L_{att} >40 cm) [2]

LuAG:Ce fiber with length 22 cm demonstrate L_{att} = 104 cm

[1] Paul Lecoq, *New crystal technologies for novel calorimeter concepts,* Journal of Physics: Conference Series 160 (2009) 012016

[2] A. Benaglia, M. Lucchini, K. Pauwels et al., *Test beam results of a high granularity LuAG fibre calorimeter prototype*. J. Instrum. 11, P05004 (2016)

Why YAG:Ce?

- **Cost of starting Y_2O_3 is powder by ~100 times lower then Lu_2O_3**

- **As YAG:Ce contains light ions, its radiation hardness under high energy hadrons is better compared to PWO and other heavy scintillators [3, 4]**

[3] E. Auffray, A. Barysevich, A. Fedorov et al., *Radiation damage of LSO crystals under c-and 24 GeV protons irradiation*. Nucl. Instrum. Methods Phys. Res. Sect. A 721, 76–82 (2013)

[4] E. Auffray, A. Barysevich, A. Gektin et al., *Radiation damage effects in Y2SiO5: Ce scintillation crystals under c-quanta and 24 GeV protons*. Nucl. Instrum. Methods Phys. Res. Sect. A 783, 117–120 (2015)

Previous research

[5]

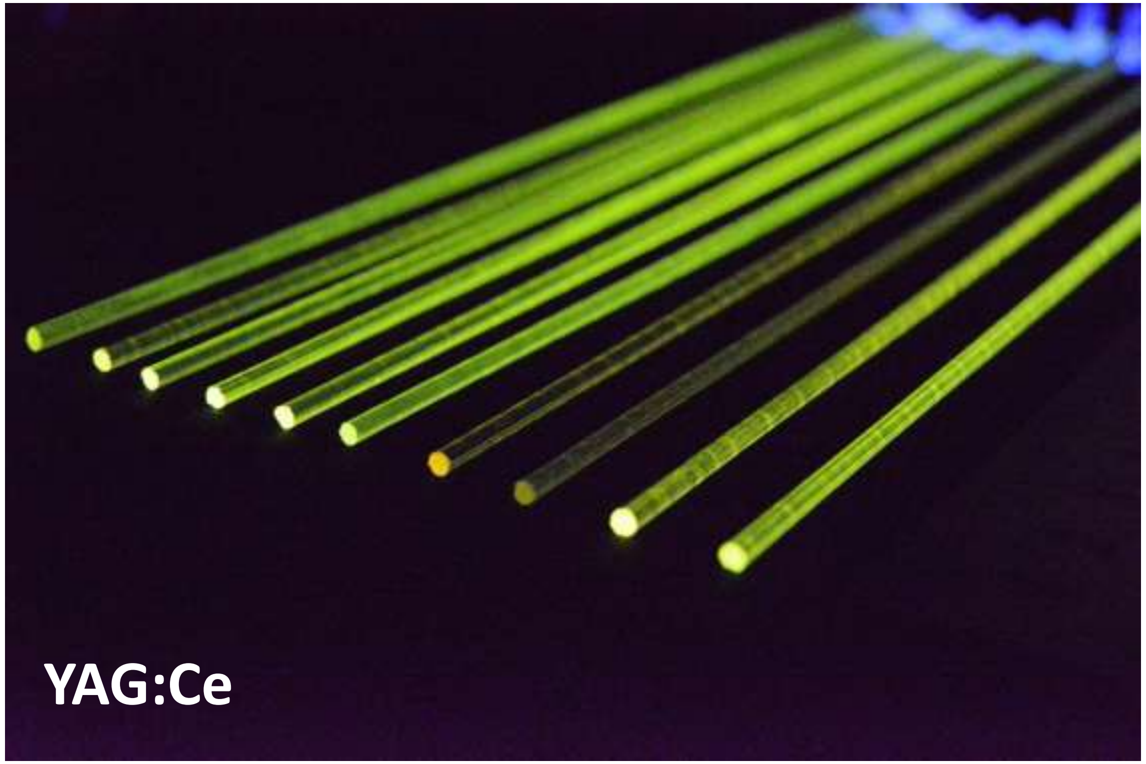
Table 1 Some results on the YAG-based fibers characterization

Sample	Shape	Orientation	Growth rate, mm/min	Ce conc, ppm	Mg conc, ppm	L_{att}, cm,	Light output, photon/MeV (tail/head)	Decay time, ns fast/slow/average,	Gas
YAGC1S	□	111	0.3	1000	–	1.7	20,900/14,900	81/151/132 tail	Ar
YCV1	○	111	0.3	150	–	18	19,900/19,900	72/224/160 tail 58/178/142 head	Ar
YCV2	○	100	0.3	150	–	18	18,900/18,500	89/245/191 tail 93/244/185 head	Ar
YCV3	□	100	0.3	150	–	16.5	20,900/19,900	70/197/143 tail 66/205/157 head	Ar
YCV4	○	111	0.3	150	100	4.5	11,900/11,900	50/126/96 tail 41/120/97 head	Ar
YCV5	○	111	0.3	150	50	12	21,600/21,600	55/190/133 tail 56/198/137 head	Ar
YCV6	○	111	0.3	100	100	2.3	16,200/16,200	46/145/112 tail 44/173/132 head	Ar
YCV7	○	111	0.3	100	50	4.4	18,300/18,300	42/139/111 tail 45/159/117 head	Ar
YCV8	○	111	0.3	100	25	6.5	20,500/20,500	49/156/114 tail 47/165/120 head	Ar
YCV9	○	111	0.3	180	50	5.02	–/–	85/233/180 tail 84/259/196 head	Ar
YCV12	○	111	0.15	150	25	6.58	–/–	96/286/210 head	ALPHAGAS
YCV13	○	111	0.2	180	25	7.59	–/–	118/280/201 tail 119/294/226 head	ARCAL
YCV14	○	111	0.2	200	120	2.63	–/–	110/275/206 tail 113/310/221 head	ALPHAGAS
YCV15	○	111	0.2	150	–	10.07	–/–	120/325/271 head	ALPHAGAS
YCV16	○	111	0.2	150	–	17.96	–/–	–/–/–	ARCAL

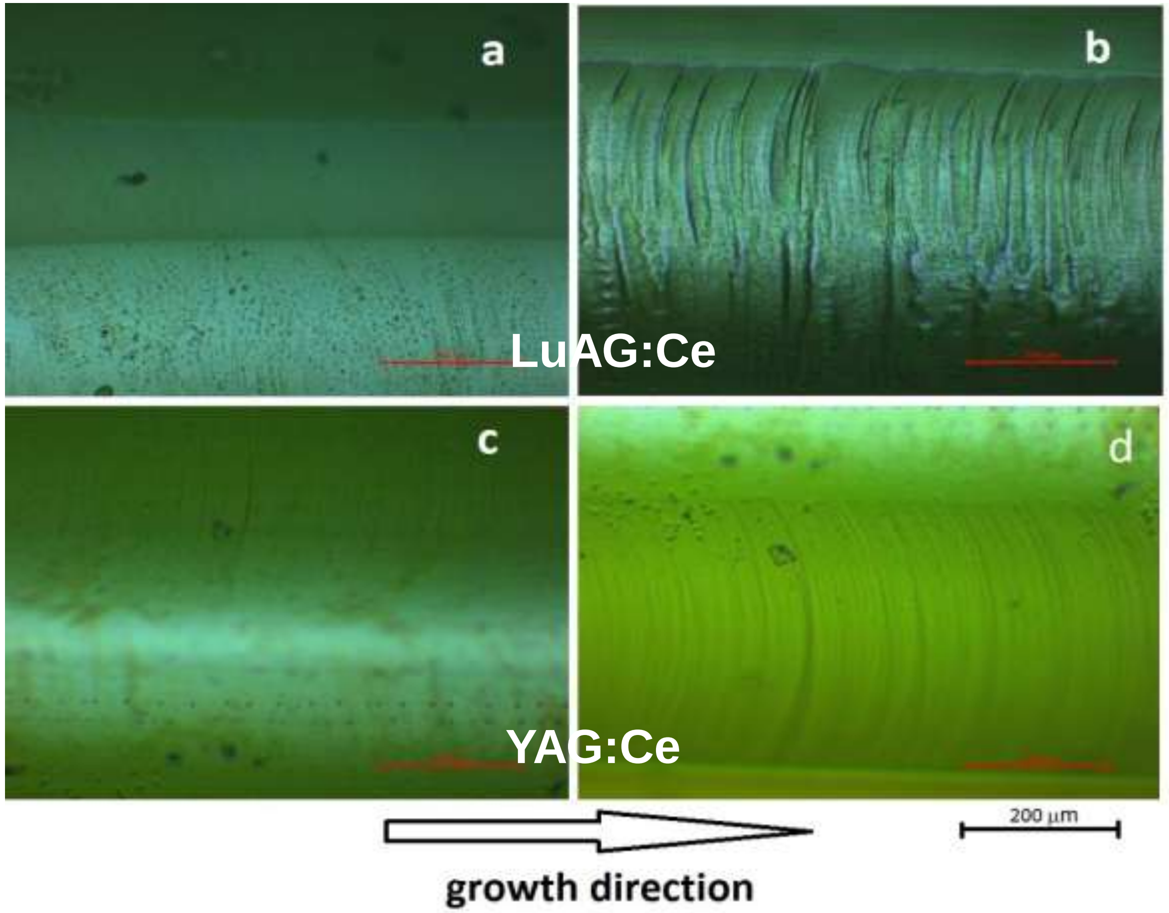
[5] V. Kononets, K. Lebbou, O. Sidletskiy, Yu. Zorenko, M. Lucchini, K. Pauwels, and E. Auffray, pp. 114-128. In: Engineering of Scintillation Materials and Radiation Technologies, M. Korzhik and A. Gektin (eds.), Springer Proceedings in Physics 200, Springer International Publishing AG 2017, 339 p.

Fabrication method of YAG fibers

m-PD furnace & crystals (ILM, Lyon, France)

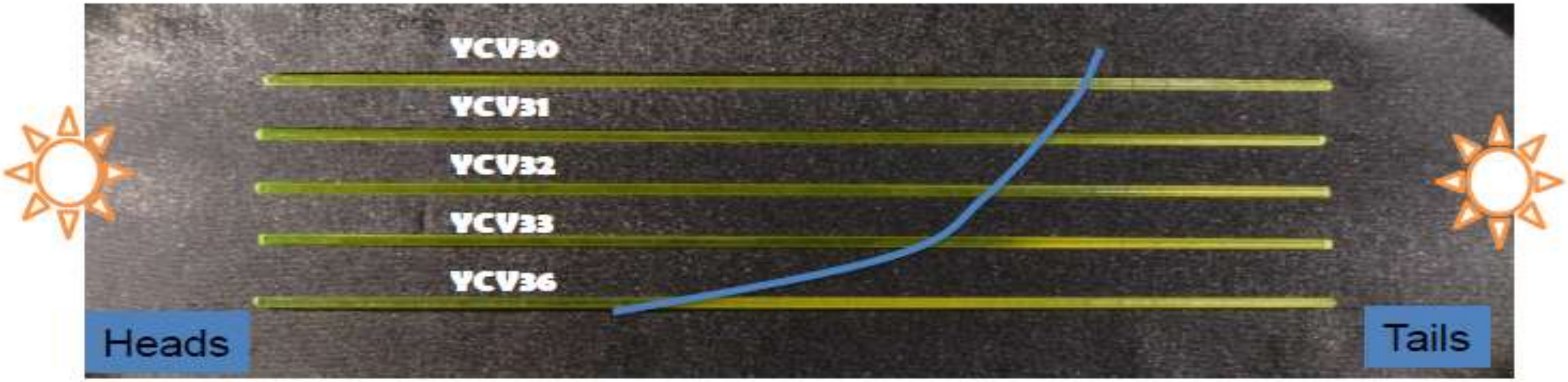


Causes of attenuation length degradation

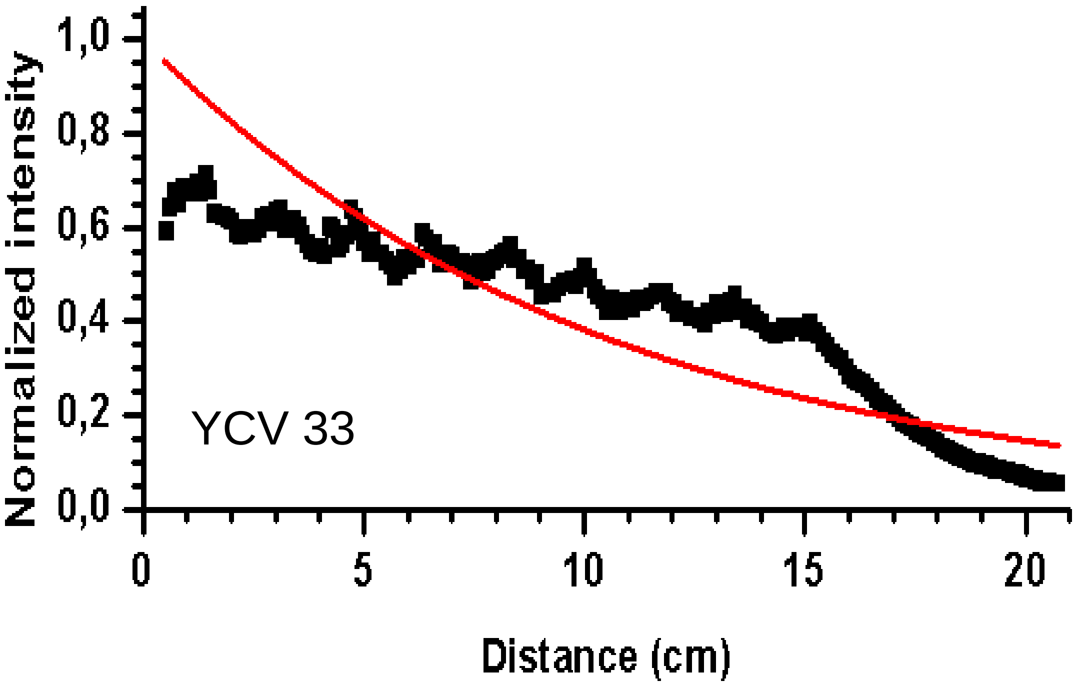


Periodical “waves” oriented perpendicular to the growth direction are formed after variation of melt meniscus shape, probably, due to supercooling at the crystallization interface and/or instable thermal conditions. Supercooling can be caused by formation of foreign phases on the crystallization interface due to Al deficiency in the melt.

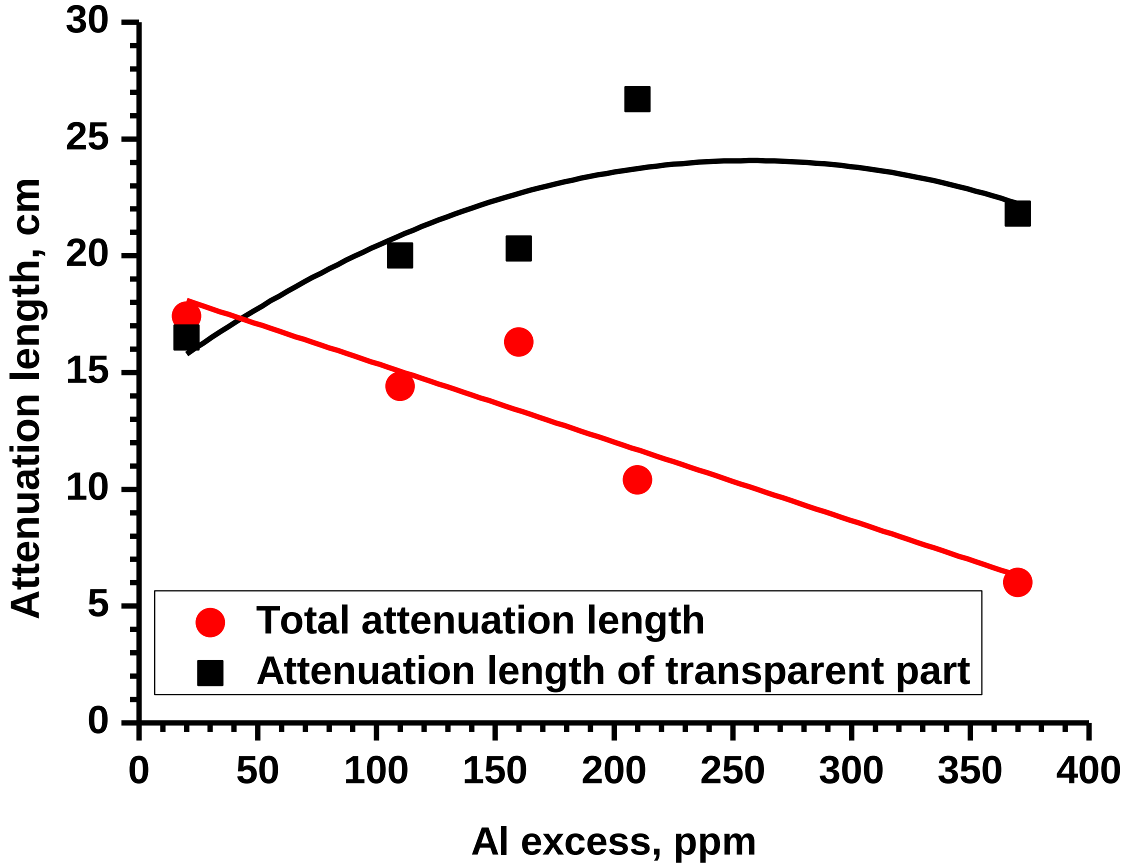
Fiber crystal growth from nonstoichiometric melt



Sample	Ce conc, ppm	Al excess, ppm	Overall L_{att}, cm	L_{att} of the transparent part, cm	Length of the transparent part, cm
YCV30	100	**<20**	17,4	16,5	22
YCV31	100	**110**	14,4	20,0	16
YCV32	100	**160**	16,3	20,3	18
YCV33	100	**210**	10,4	26,7	15
YCV36	100	**370**	6,0	21,8	11



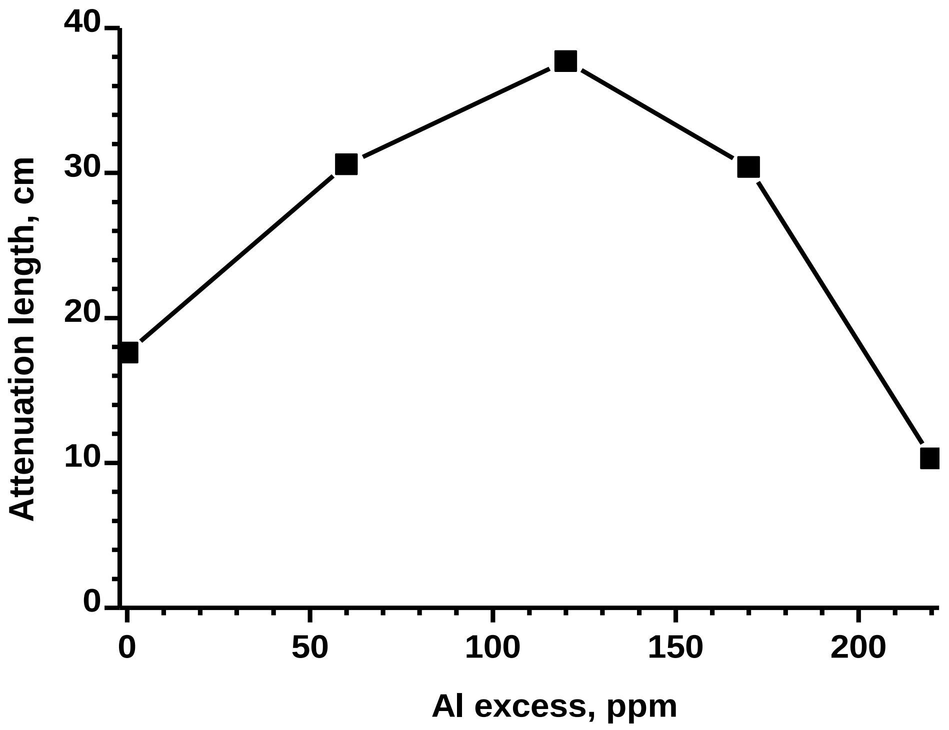
Attenuation length vs. Al excess



Optimal concentration interval of Al excess lies below 400 ppm and provides the improvement of attenuation length in the head part of the fibers.
Fibers grown by μ-PD method providing a large melt surface/bulk ratio, Al2O3 evaporation is a notable factor determining the quantity of macrodefects in fibers.

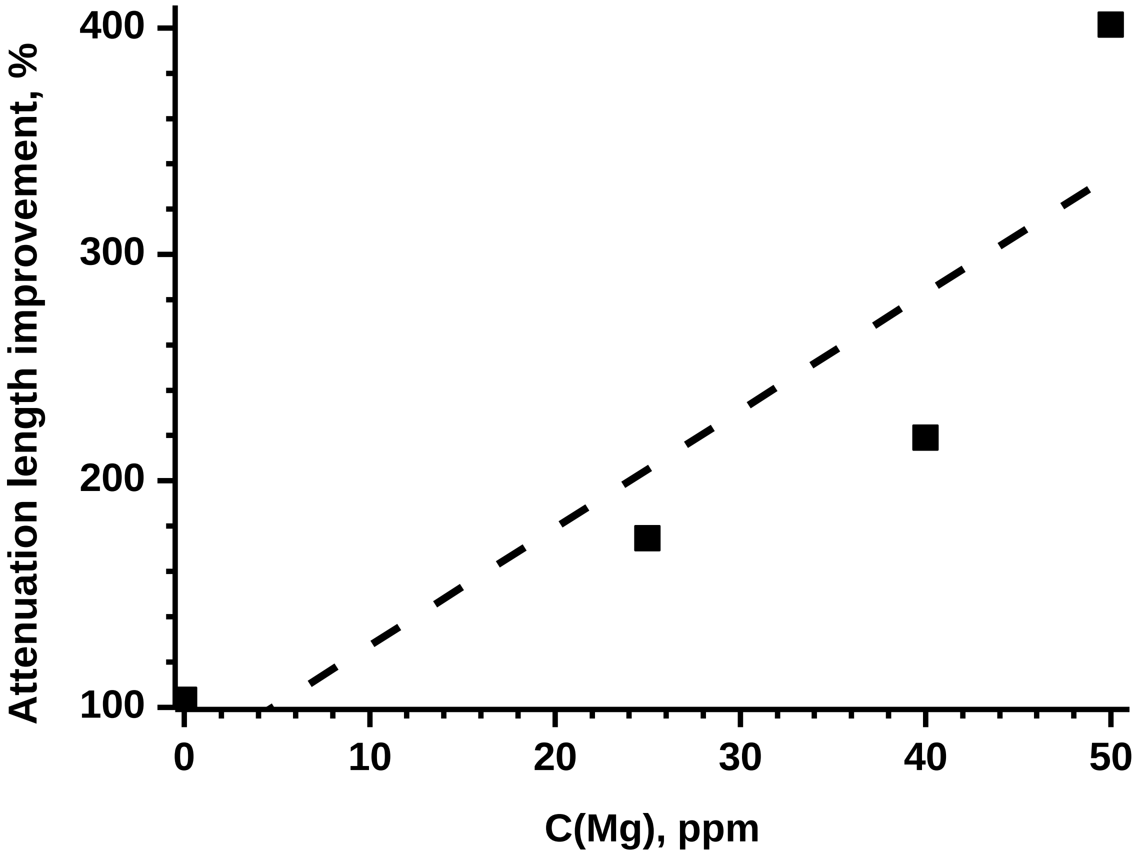
Obtaining of 22 cm long transparent fibers

- vertical thermal gradient at the crystallization interface was increased;
- melt pressure inside the capillary die was increased.



Name	C(Al_{doped}), Ppm	C(Mg), Ppm	Attenuation length, cm
YCD10	0	20	24.3
YCD7	0	40	35.7
YCD11	170	20	6.2
YCD9	170	40	4.2

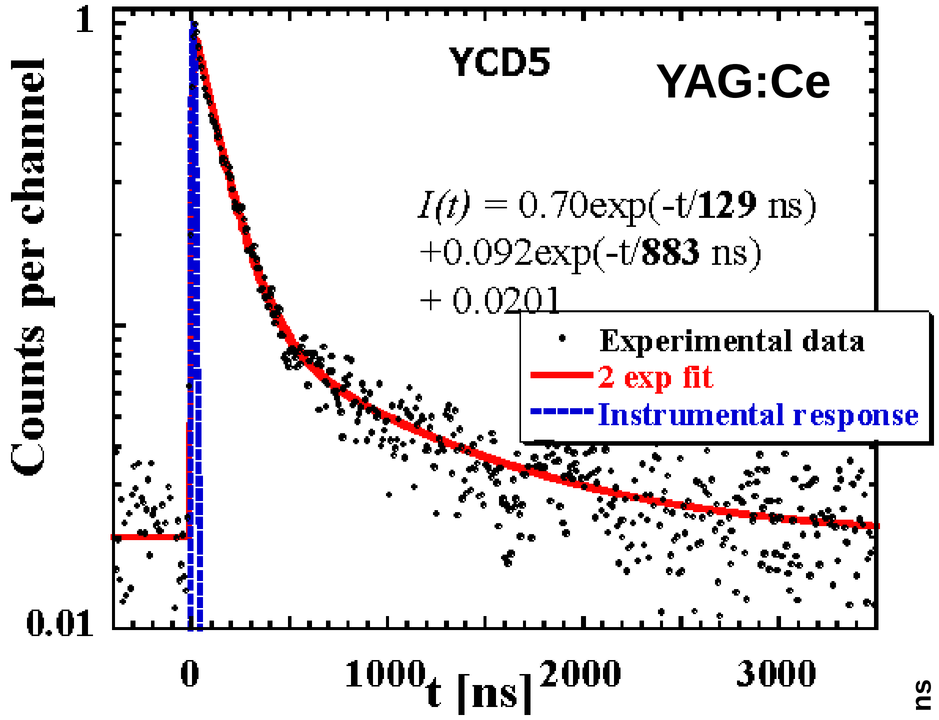
Effect of thermal treatment of fibers

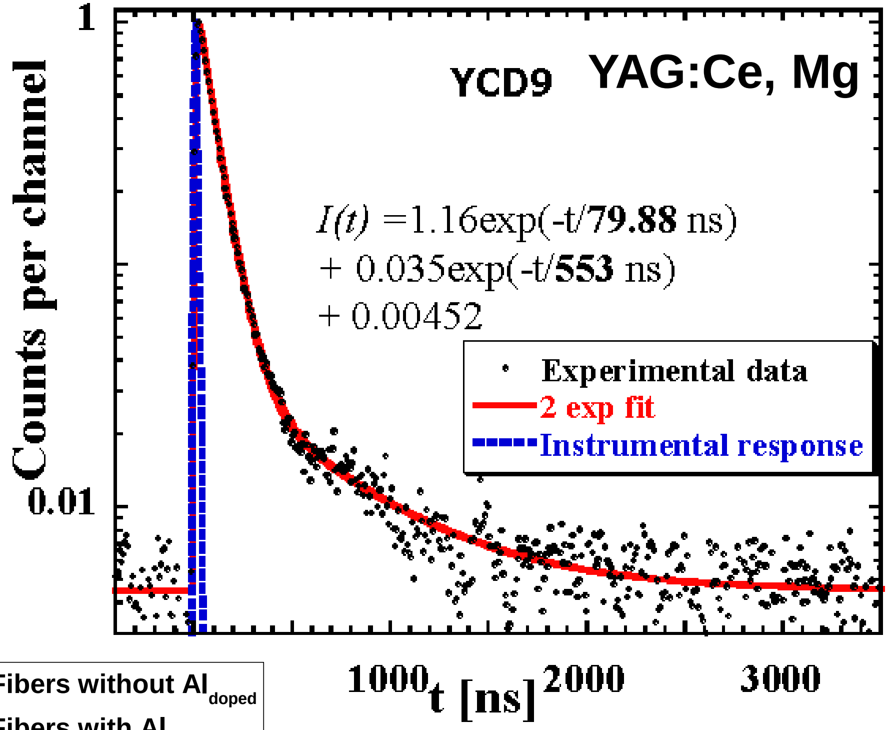


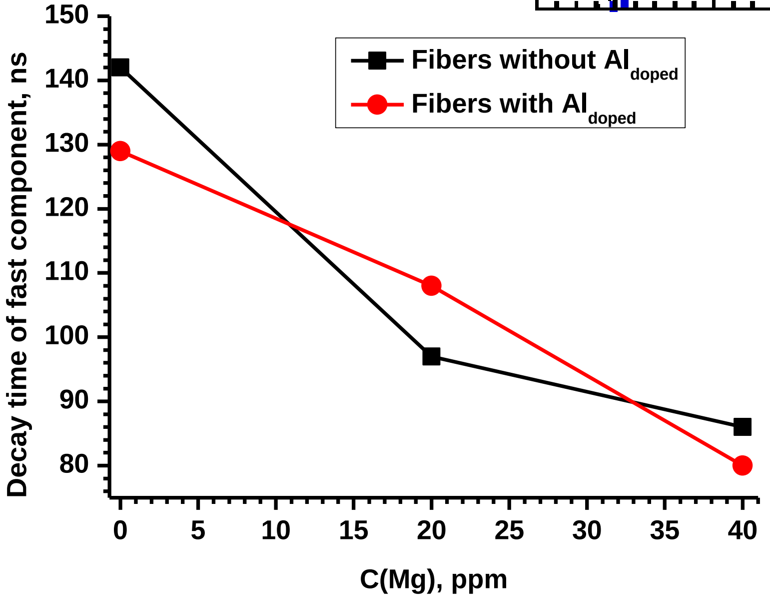
Post-growth annealing of YAG:Ce fibers in air at 1200 C did not give a reproducible positive result.

Meanwhile, for Mg-doped fibers the effect of thermal annealing is significant and increases with Mg concentration .

Decay time reducing







Summary

- The significant progress in transmission of YAG:Ce-based fibers has been achieved by adding of Al^{3+} excess into the melt and optimizing thermal conditions of crystallization by the μ-PD method. As the result, the attenuation length of up to 38 cm was achieved in 22 cm long YAG:Ce fibers.
- Optimization of thermal conditions and post-growth annealing provided the attenuation length enhancement up to 36 cm in YAG:Ce,Mg, which practically meets the requirement of detectors for future colliders.
- The scintillation decay time of the main fast component decreases from 130 to 80 ns with light Mg codoping.

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Thank you for the attention