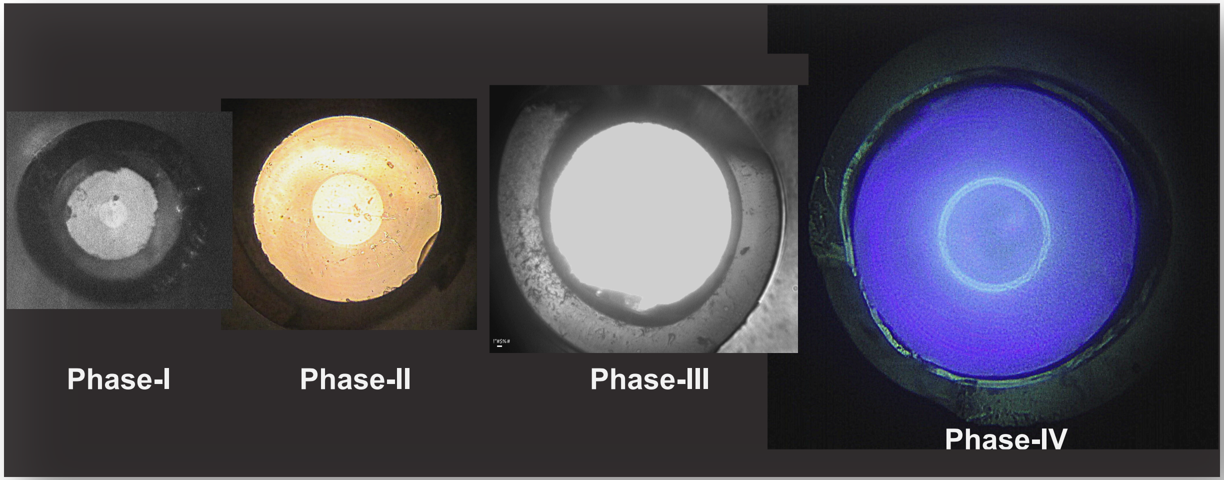
Cerium-doped Fused-Silica Fibers



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Motivation

- Radiation-hard "hybrid" fibers
  - Scintillation: "ionization" signal in present/future detectors for high-energy physics experiments
  - Cherenkov: "radiation" signal in calorimetry and timing applications in various "complementary" detectors
- Radiation-hard wavelength shifter (WLS) fibers
  - Good spectral match with CeF_3 crystal (F. Nessi-Tedaldi's talk this conference)
  - Ce^{3+} *vs* Ce^{4+}
- Example: Dual- and triple-readout calorimeter
  - Scintillation (hydrogenous) + Cherenkov -> Dual-readout calorimetry where event-by-event measurement of *S* and *Q* reduces the contribution from large fluctuations in pi-zero production in hadron showers in energy measurement
  - Scintillation (non-hydrogenous) + Scintillation (hydrogenous) + Cherenkov -> Triple-readout where the comparison of signals from two scintillation media will help reduce contributions from fluctuations in neutron production
- Other applications
  - Homeland security, dosimetry, oil exploration, *etc.*

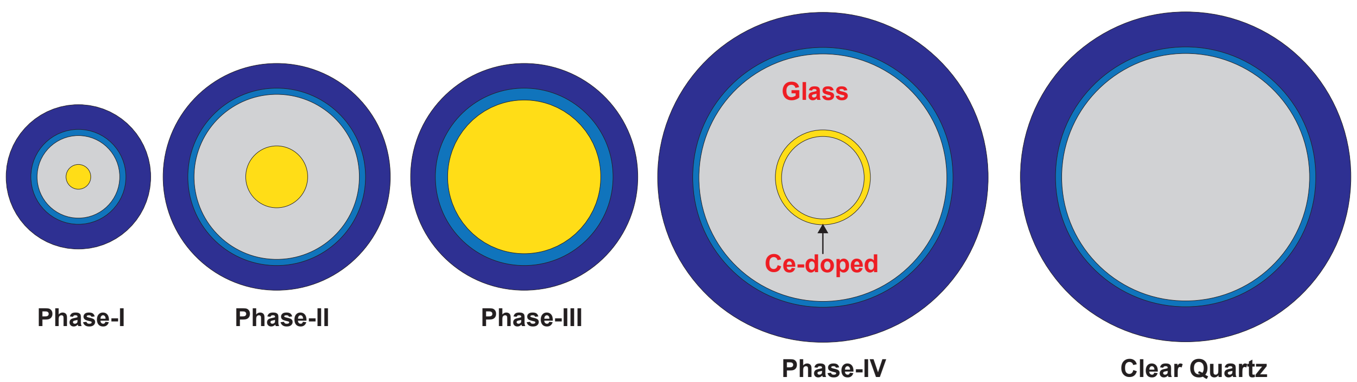
Fiber Configurations

We studied different types of Ce-doped fibers in the last two years but we limit the presentation to four industrially produced samples

All fibers (Ce-doped and clear) were produced by Polymicro Technologies LLC, Phoenix, AZ

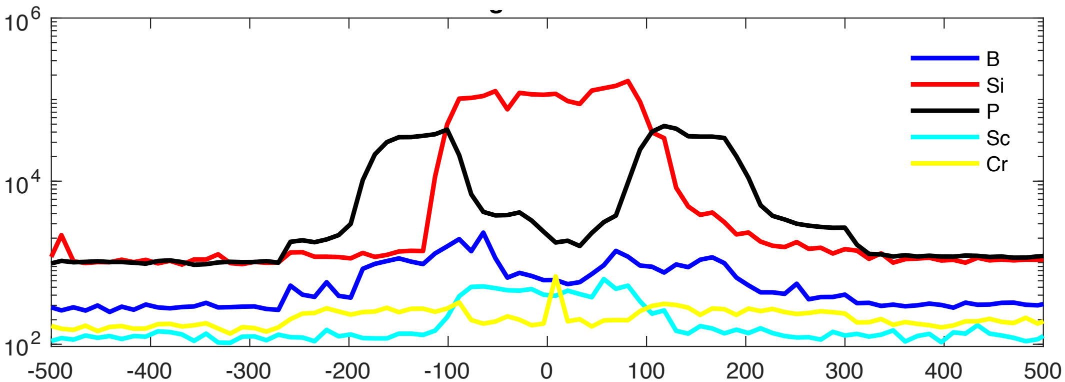
All fibers are hard-polymer clad and acrylate buffer. The "glass" part is (high OH^-) fused synthetic silica

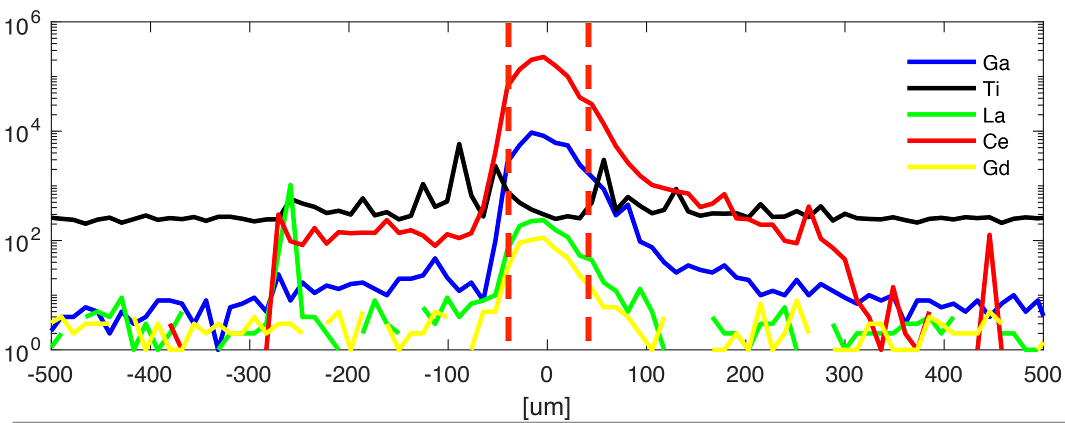
Fiber Name	Core OD [μm]	Glass OD [μm]	Clad OD [μm]	Buffer OD [μm]
Phase-I	60±7	200±6	230^{+5}_{-10}	350±15
Phase-II	150±20	400±10	430±10	550±30
Phase-III	370±8	-	400 ±8	550±15
Phase-IV	200(clear)/15(doped)	600±6	630±10	800±30
Clear quartz	600±10	-	630^{+5}_{-10}	800±30

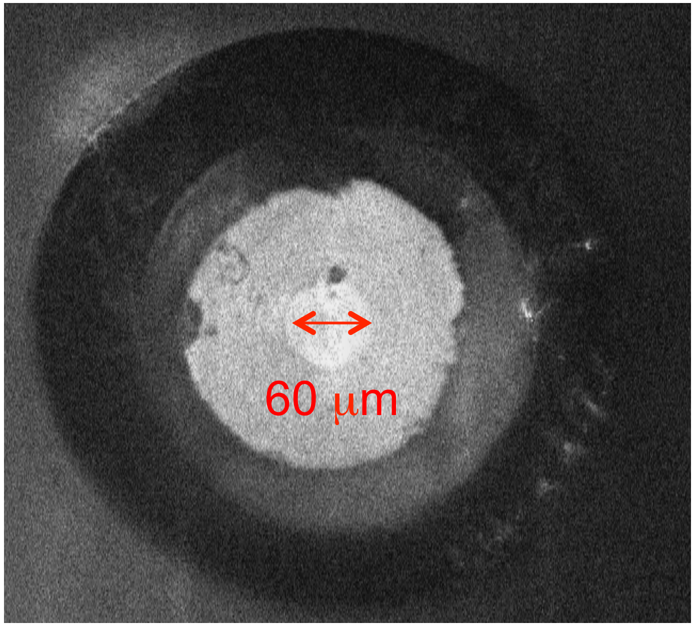


Mass Spectroscopy Analyses - Phase-I

The mass spectroscopy analysis is using laser ablation inductively-coupled plasma quadrupole mass spectrometer. The laser spot size 40 μm in diameter and the scan rate is 10 μm/s. We concentrate on the Ce-doped regions in lower plot.







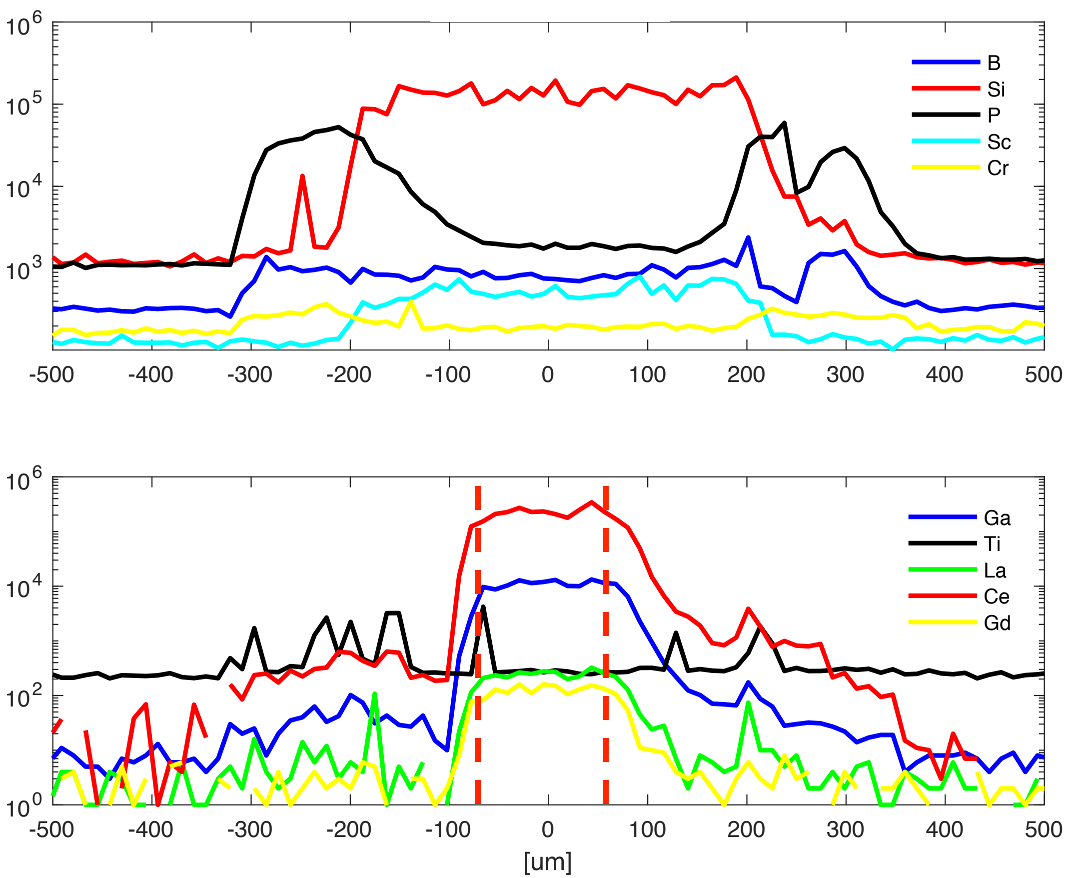
Clad: P, B, Cr

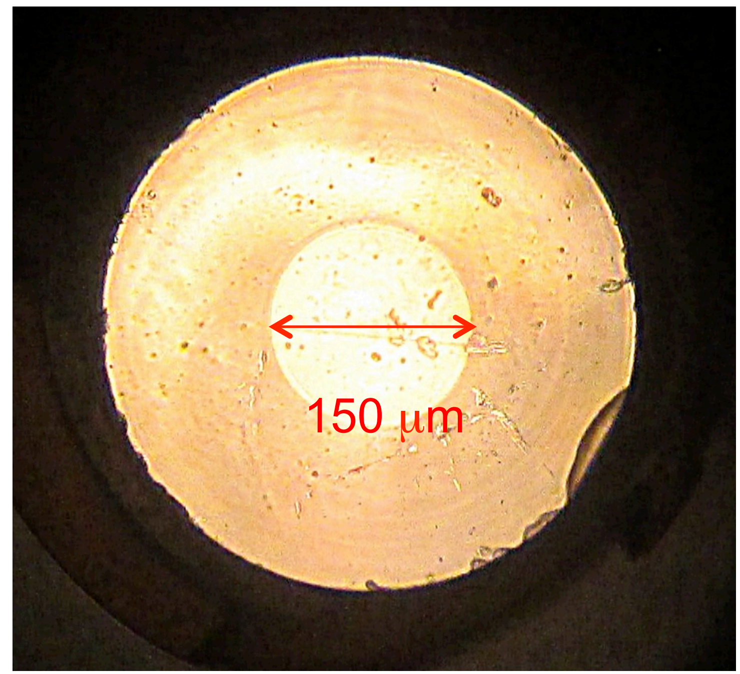
Glass: Si, Sc

Ce-doped: Ce, Ga, La, Gd

Mass Spectroscopy Analyses – Phase-II

Phase-II fiber is chemically identical to Phase-I fiber but larger overall dimensions.





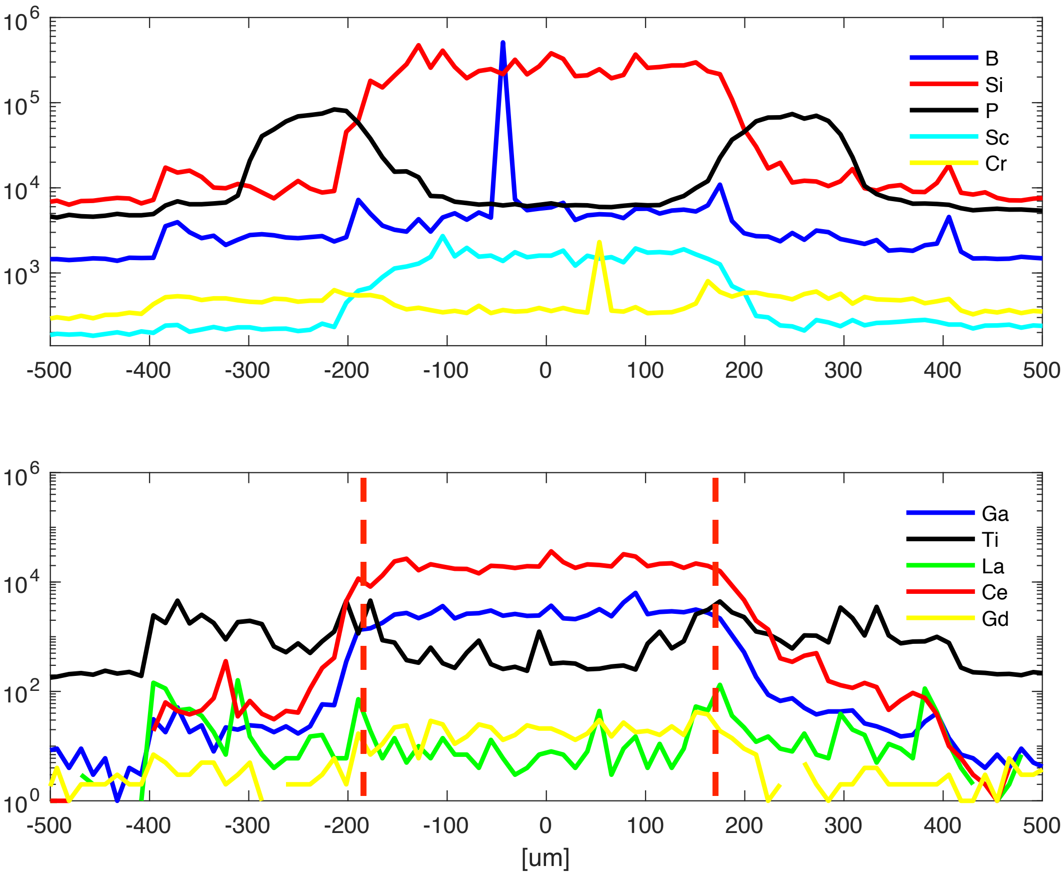
Clad: P, B, Cr

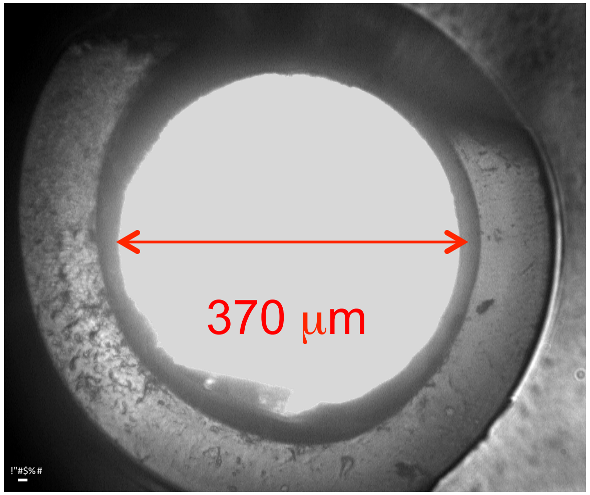
Glass: Si, Sc

Ce-doped: Ce, Ga, La, Gd

Mass Spectroscopy Analyses – Phase-III

Phase-III fiber does not have clear quartz region.





Clad: P, B, Cr

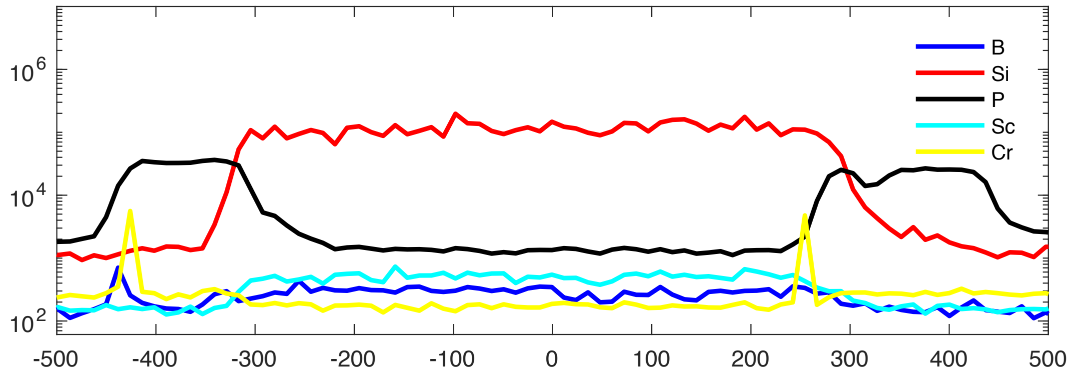
Ce-doped: Ce, Ga, Gd

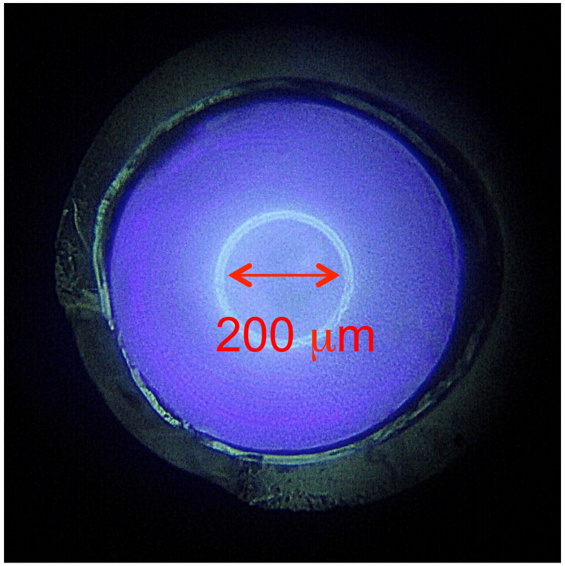
Mass Spectroscopy Analyses – Phase-IV

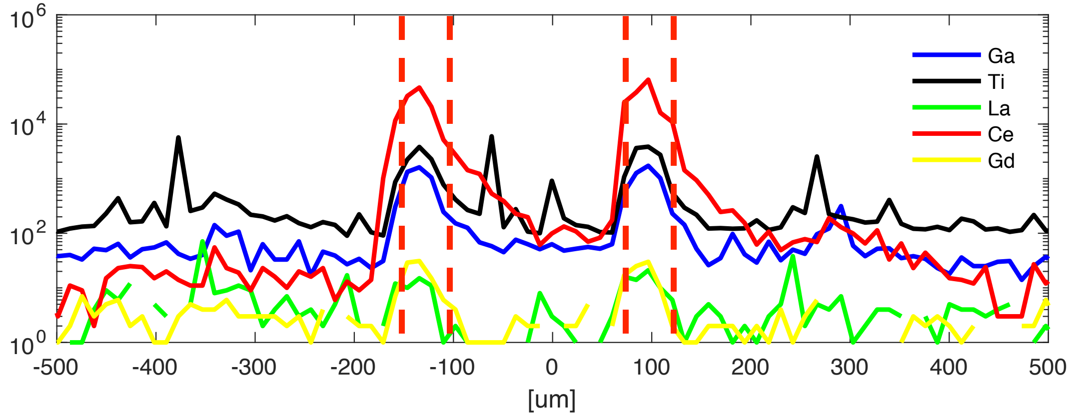
Clad: P, Cr

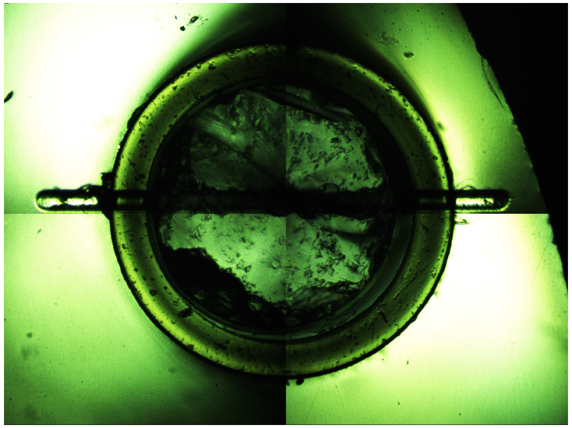
Glass: Si, Sc, B

Ce-doped: Ce, Ti, Ga, Gd







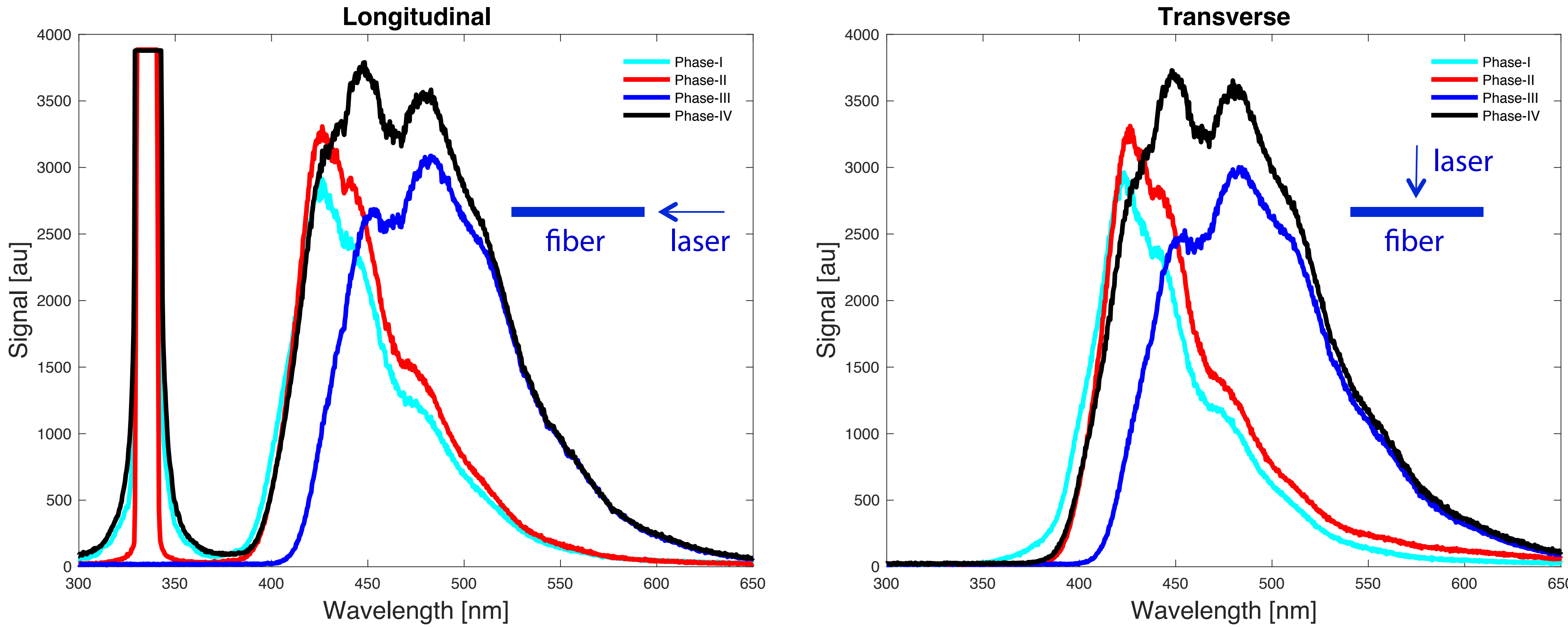


Mass Spectroscopy Analyses – Summary (ppm)

Fiber	B	Mg	Al	P	Ca	Sc	Ti	Cr	Fe	Ga	Zr	La	Ce	Gd
Phase-I doped	-	2	13,760	183	0.02	5	-	5	-	176	0.3	1	5,780	9
Phase-I glass	6	-	11	70	-	6	-	-	-	-	-	-	10	-
Phase-II doped	4	-	12,700	154	-	5	-	-	-	160	0.2	1	4,920	7
Phase-II glass	3	6	11	97	-	6	-	-	-	-	-	-	4	-
Phase-III doped	59	107	188	862	0.05	5	1	11	145	12	1	0.1	331	0.4
Phase-III clad	223	676	5,292	80,506	302	19	25	371	3,838	16	74	4	302	-
Phase-IV core	7	160	53,174	2,430	0.1	3	1	22	225	3	2	0.06	87	0.2
Phase-IV ring	4	37	6,826	32	0.02	3	4	-	-	14	0.1	0.09	1,006	1
Phase-IV clad	162	6,972	1,736,993	218,539	4	-	23	1,053	-	24	7	19	41	-
Clear Quartz	7	-	-	94	-	6	-	-	-	-	0.1	-	-	-

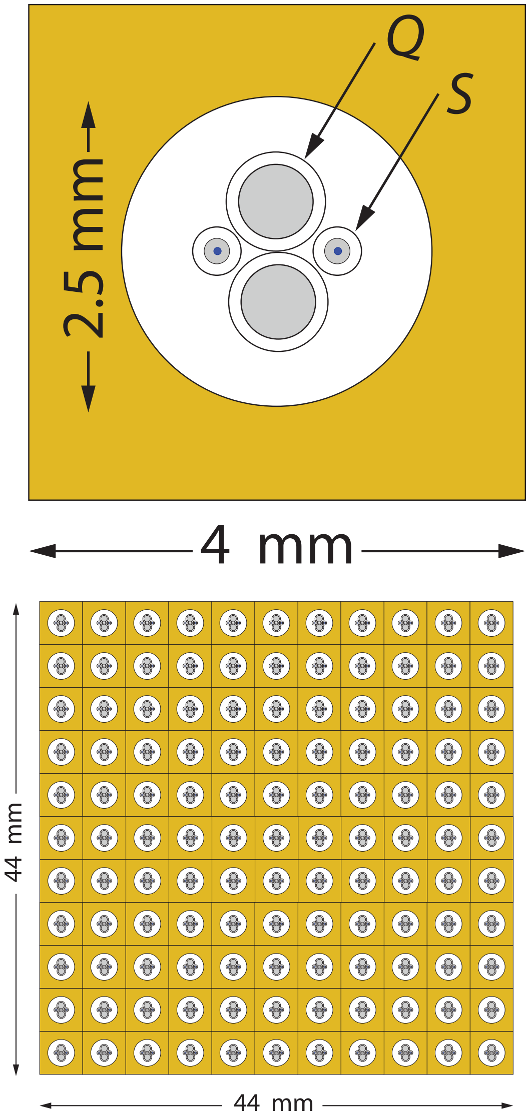
- Clear quartz (fused-silica) fiber is extremely pure and radiation-hard (*e.g.* CMS forward calorimeter)
- With cerium other elements are also necessarily introduced to the fiber core (Ga, La, Gd, …)
- Aluminum is a common agent against clustering of dopants in silica but not favored for the purpose of radiation-hardness
- P, B, and Cr are found in clad/buffer (polymer) of all fibers

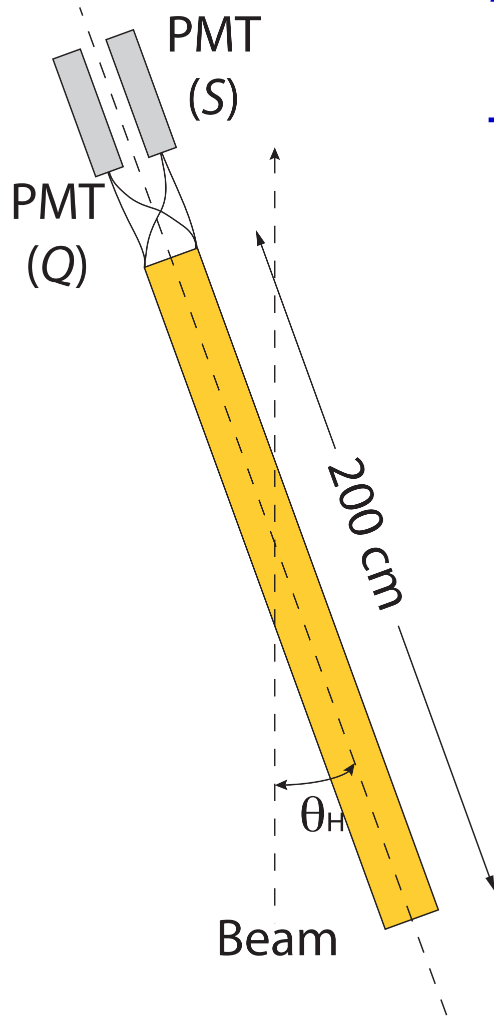
Spectral Characteristics (PL)



- Phase-I fiber is excited by a pulsed N_2 laser (337 nm) and photon emission (photoluminescence) peaks at 440 nm with a long tail
- When the laser light is injected coaxially with the fiber (longitudinal), one can clearly observe the transmission of UV light through the clear quartz parts of fibers (Phases-I, II and IV)
- Self-absorbtion "edge" is evident in the doped part (Phase-III)

Are These Fibers any Good for a HEP Detector?





A very crude "calorimeter" using Phase-I fibers

This setup was exposed to 4 to 32 GeV positrons at the MTest beamline at Fermilab to perform various measurements:

- Pulse shape
- Timing characteristics of Phase-I fiber
- Scintillation light yield
- Light propagation speed
- Optical attenuation length

Experimental Setup at MTest at Fermilab

- The module was installed on a movable table
- The angle between the beam direction and the fiber axis was set at 2, 90 and 182 degrees
- Trigger counters 1 cm x 1 cm
- Cherenkov and Phase-I fiber bundles were separately readout by two PMTs
- Signals were digitized at 5 GHz by a CAEN DRS unit (V1742)

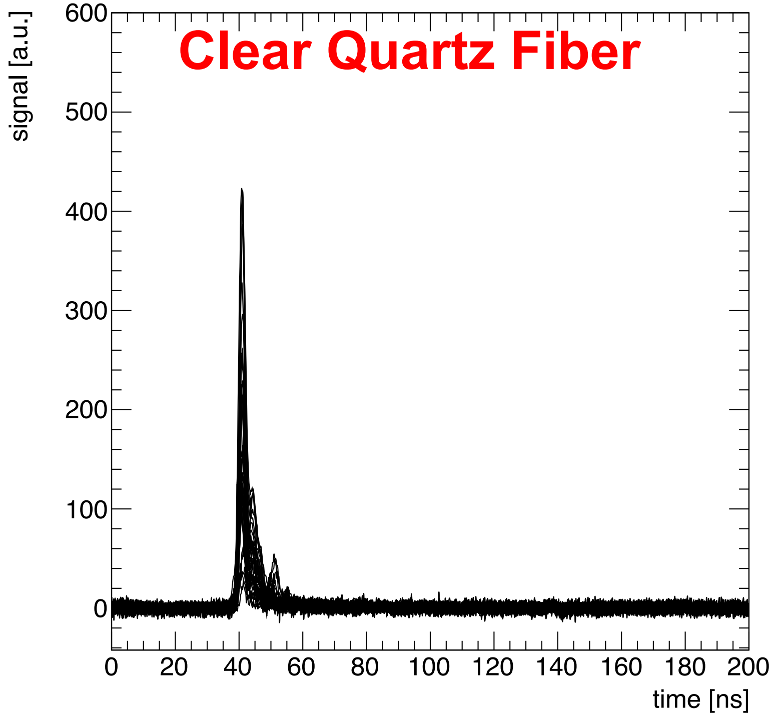
Comparison of Cherenkov & Scintillation Light

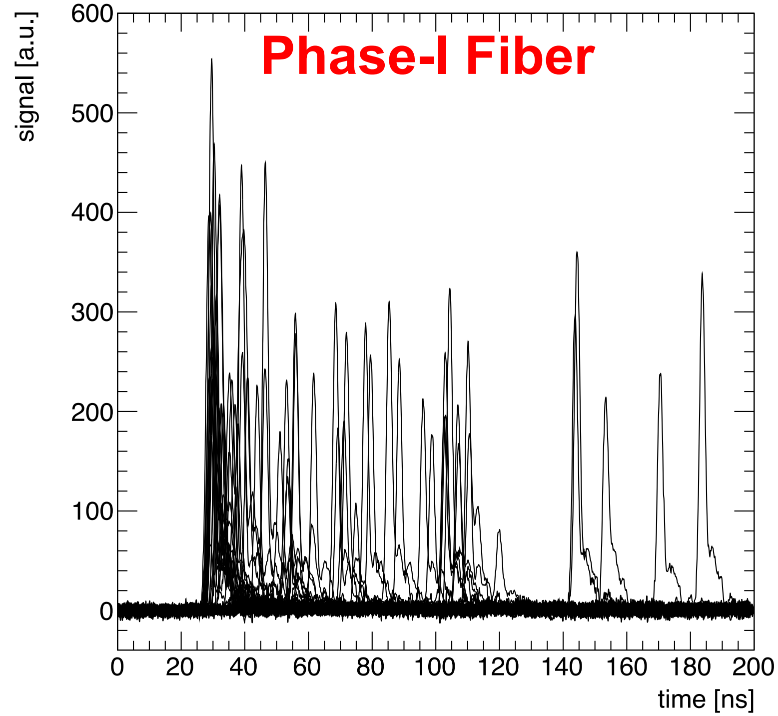
Clear scintillation and Cherenkov signals are observed from Ce-doped Phase-I fiber

Scintillation light is not as "prompt" as Cherenkov light

Small packing fraction (Ce-doped core) results in low scintillation light output (500-900 ph/MeV)

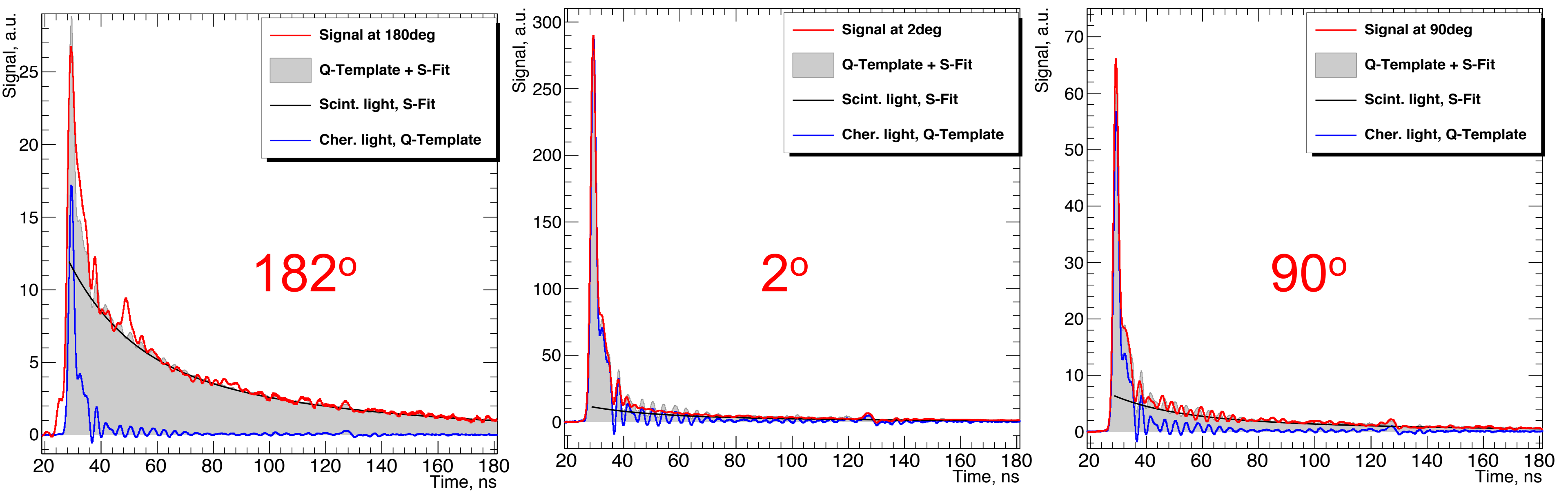
By volume: Cu 71.7%, air 20.2%, 3.5% clear quartz, 0.035% Ce-doped core, and 0.35% glass in Phase-I fiber





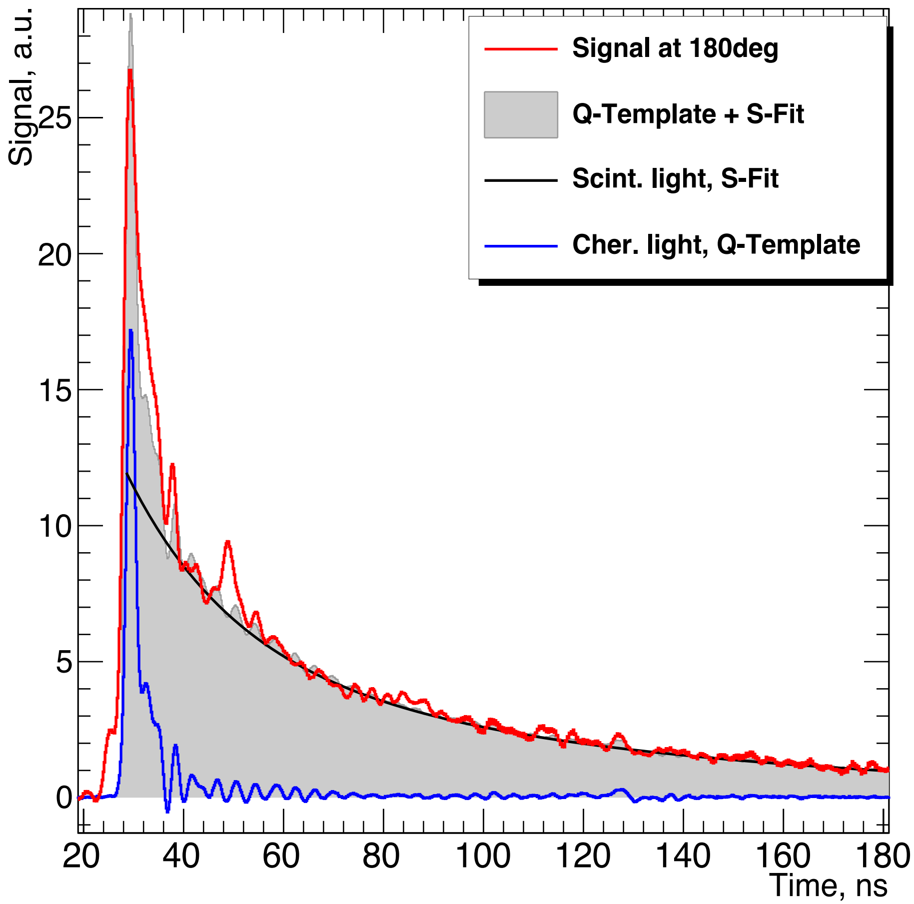
Scintillation & Cherenkov Light from Phase-I Fiber

- Light from Phase-I is an admixture of scintillation and Cherenkov photons
- While the emission of scintillation photons is isotropic, the capture of the Cherenkov photons inside the fiber depends on the angle between the fiber axis and the direction of the beam particle



Scintillation Pulse Shape Phase-I Fiber

$$S(t) = a_1 \exp\left(-t/\tau_1\right) + a_2 \exp\left(-t/\tau_2\right)$$



If parameterized as a sum of two exponentials, the relative contributions are

- Fast component:

$\tau_1 = 20.8 \pm 5.4$ ns

23.9±5.3%

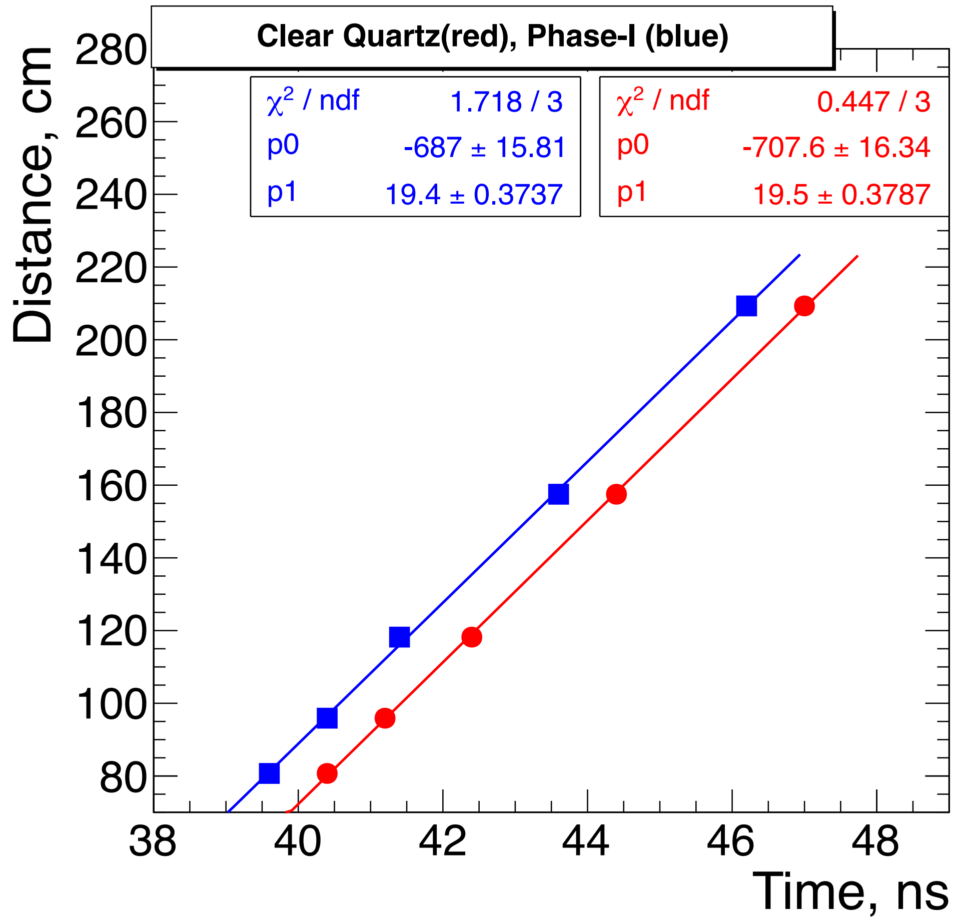
- Slow component:

$\tau_2 = 93.0 \pm 12.6$ ns

76.1±5.3%

Light Propagation Speed in Phase-I Fiber

The fibers were positioned normally (90°) with respect to the beam direction. Each data point represents the time difference between the time of trigger and the time of arrival of the signal (time-over-threshold) at the PMT.



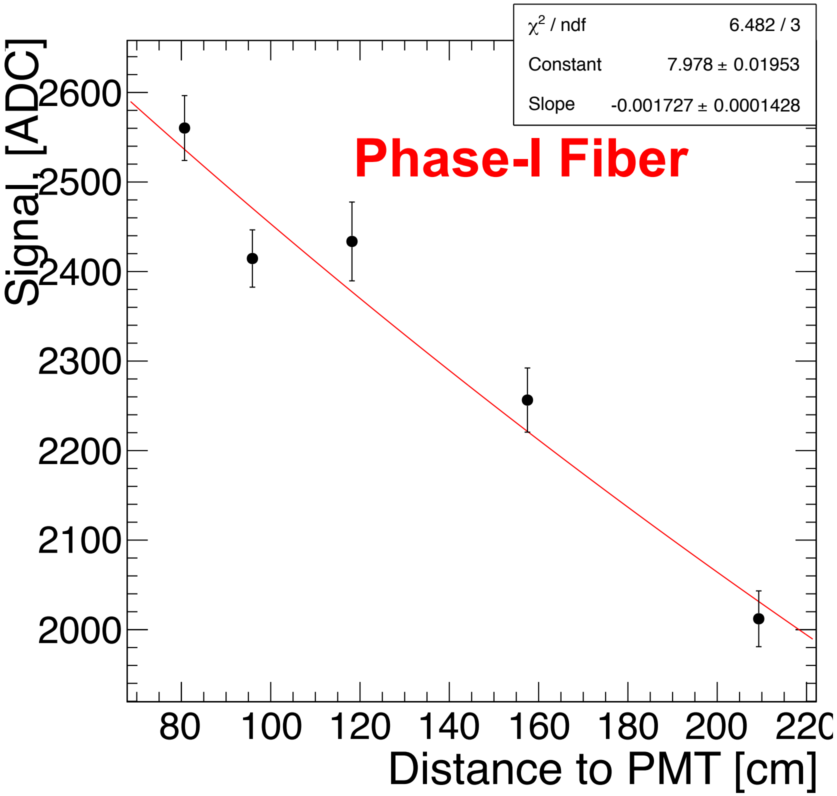
Phase-I:

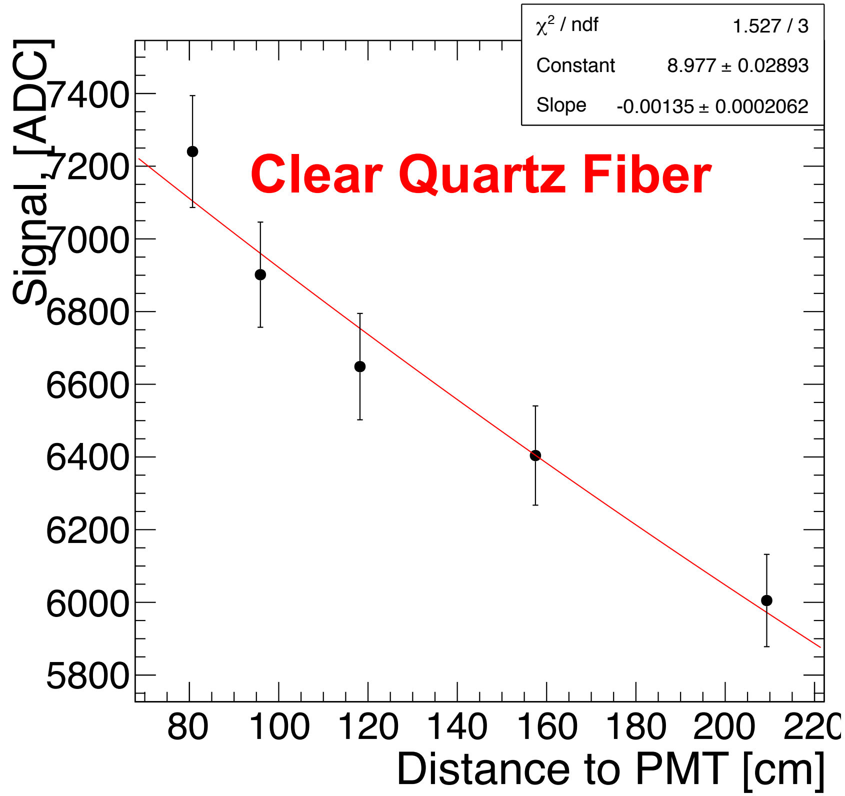
19.4 ± 0.4 cm/ns

Clear quartz:

19.5 ± 0.4 cm/ns

Optical Attenuation Length Phase-I Fiber





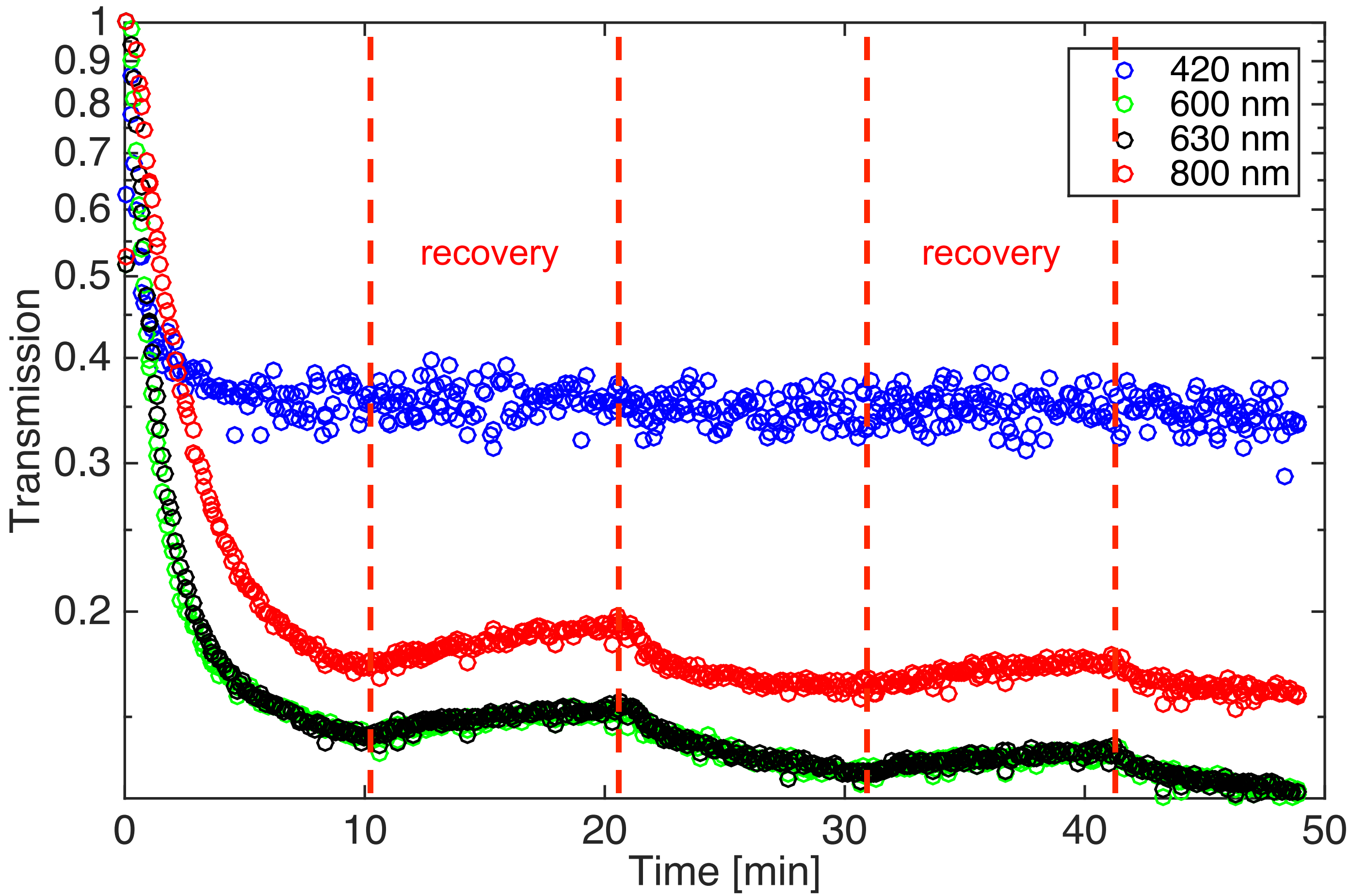
$$S(t) = S_0 \exp\left(-x/\lambda_S\right)$$

$$\lambda_S = 5.8 \pm 0.7\mathrm{m}$$

$$Q(t) = Q_0 \exp\left(-x/\lambda_Q\right)$$

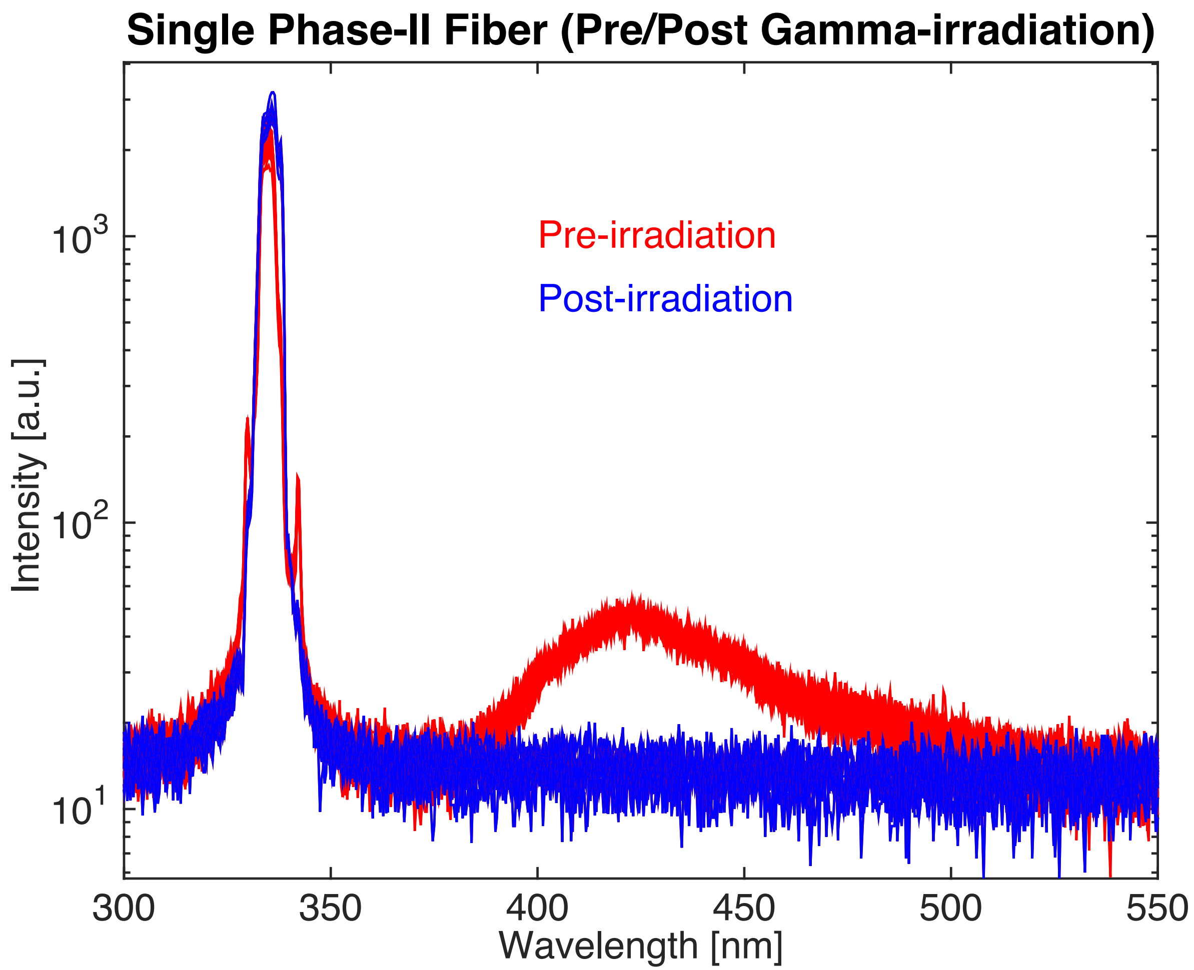
$$\lambda_Q = 7.4 \pm 0.5\mathrm{m}$$

Radiation Hardness - I



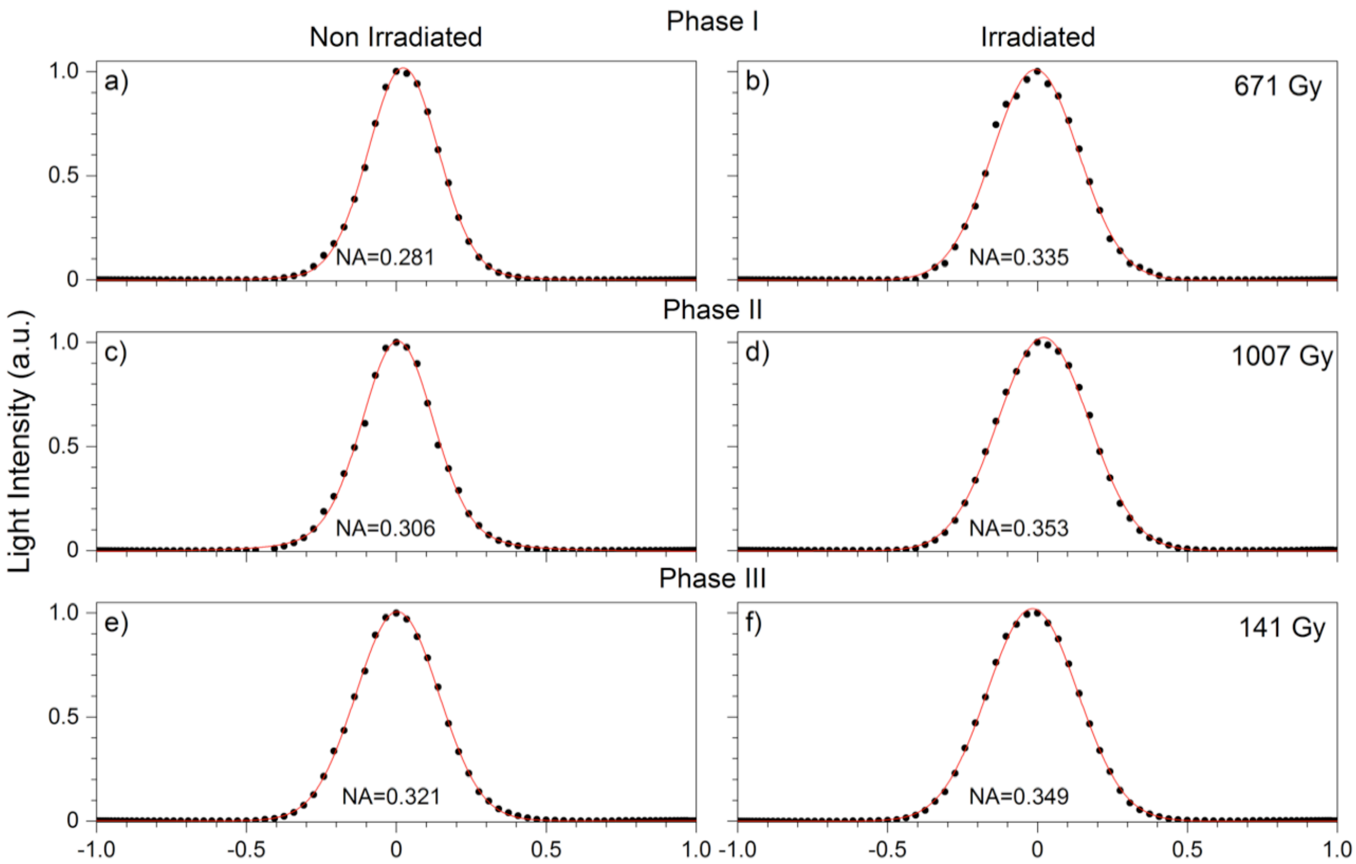
A snapshot of radiation damage and recovery for transmission with Phase-I fiber irradiated with ^{60}Co at ~1kGy/hr

Radiation Hardness - II



Loss of photoluminescence after irradiation (p 9) but not transmission (337 nm) using a N_2 laser

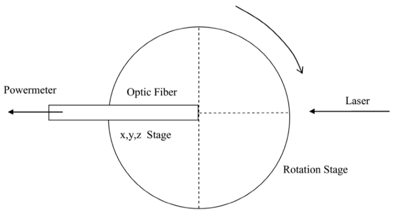
Changes in "Effective" Numerical Aperture



~19%

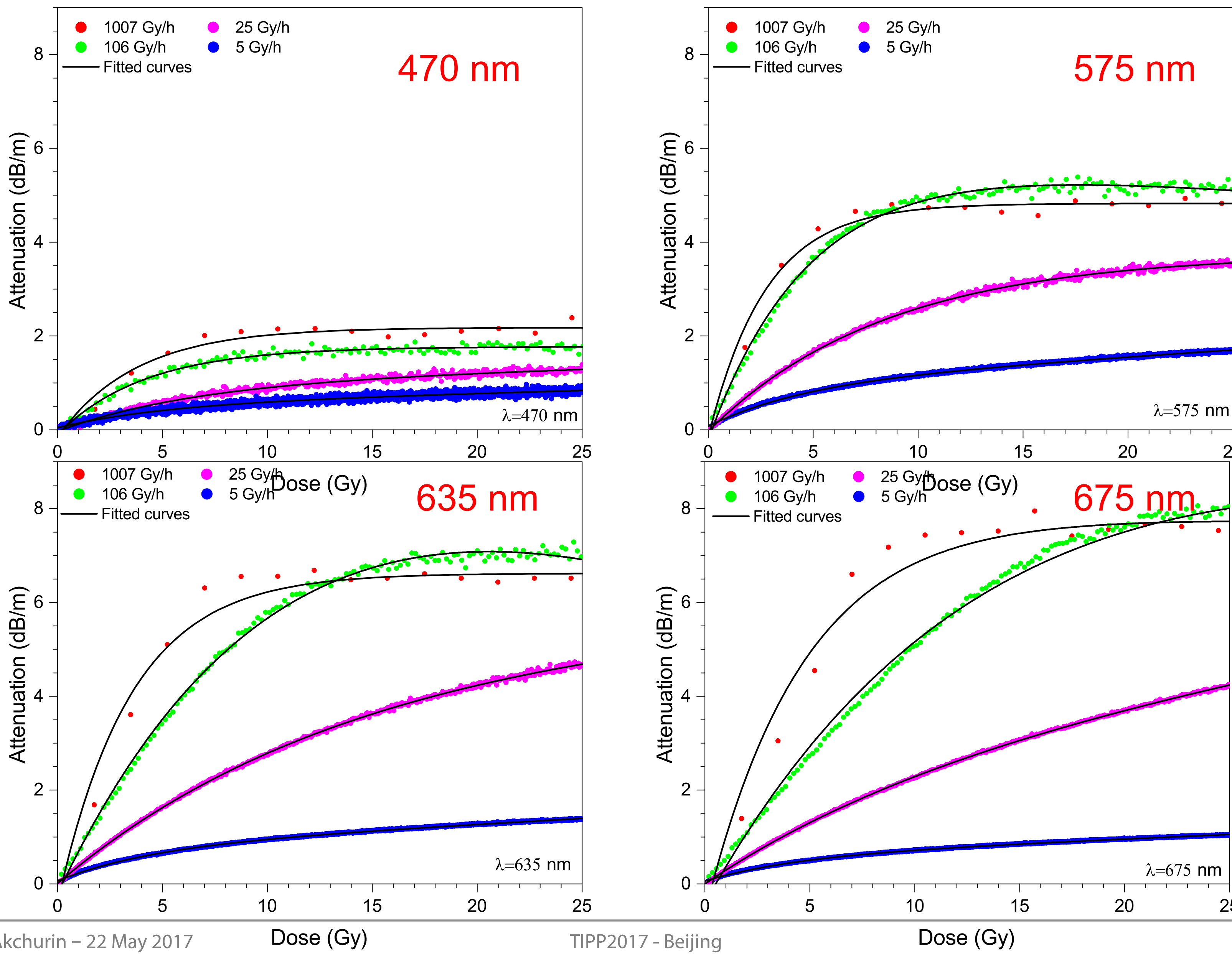
~15%

~9%

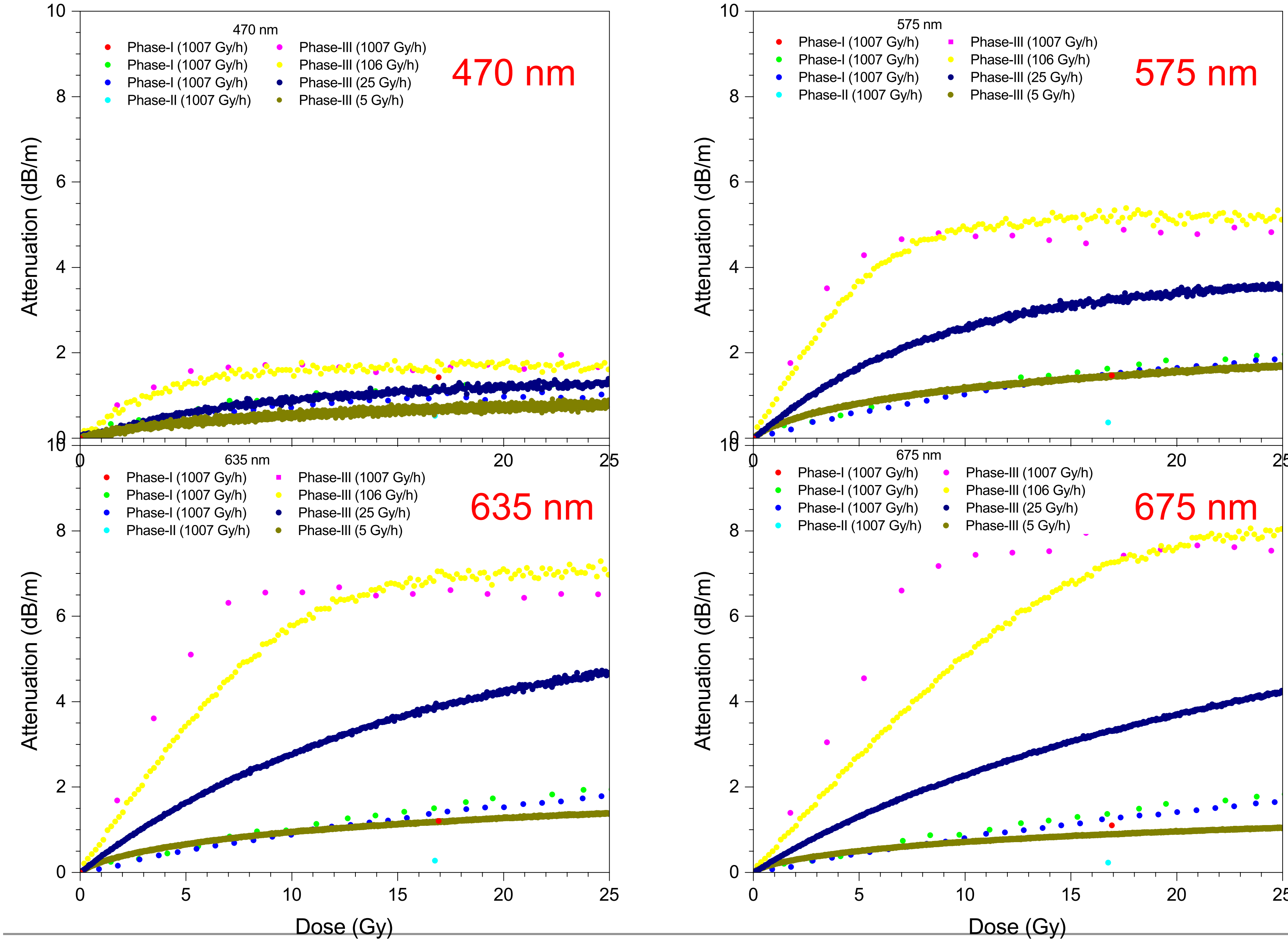


There is a clear increase in "effective" numerical aperture with the accumulated dose (~10-20%).

Phase-III Dose Rate Effect



Comparison of Phase-I, -II and -III



Summary and Conclusions

We continue studying the light emission and transmission characteristics of cerium-doped fused-silica fibers as a potential active element (pulse shape, decay time, light yield, propagation speed, WLS, attenuation length, *etc*) in detectors

Hybrid fiber structure ("clear"+"doped") may prove useful in some detector applications in HEP

Attention is paid to reproducibly manufacture fibers in an industrial setting

Although there is much remains to be understood, we have a good start in investigating radiation-hardness characteristics of cerium-doped fibers

Fundamental understanding of radiation-damage in optical waveguides is difficult and parametrizations are not always applicable/useful from one type of fiber to another

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