Cerium-doped fused-silica fibers for particle physics detectors

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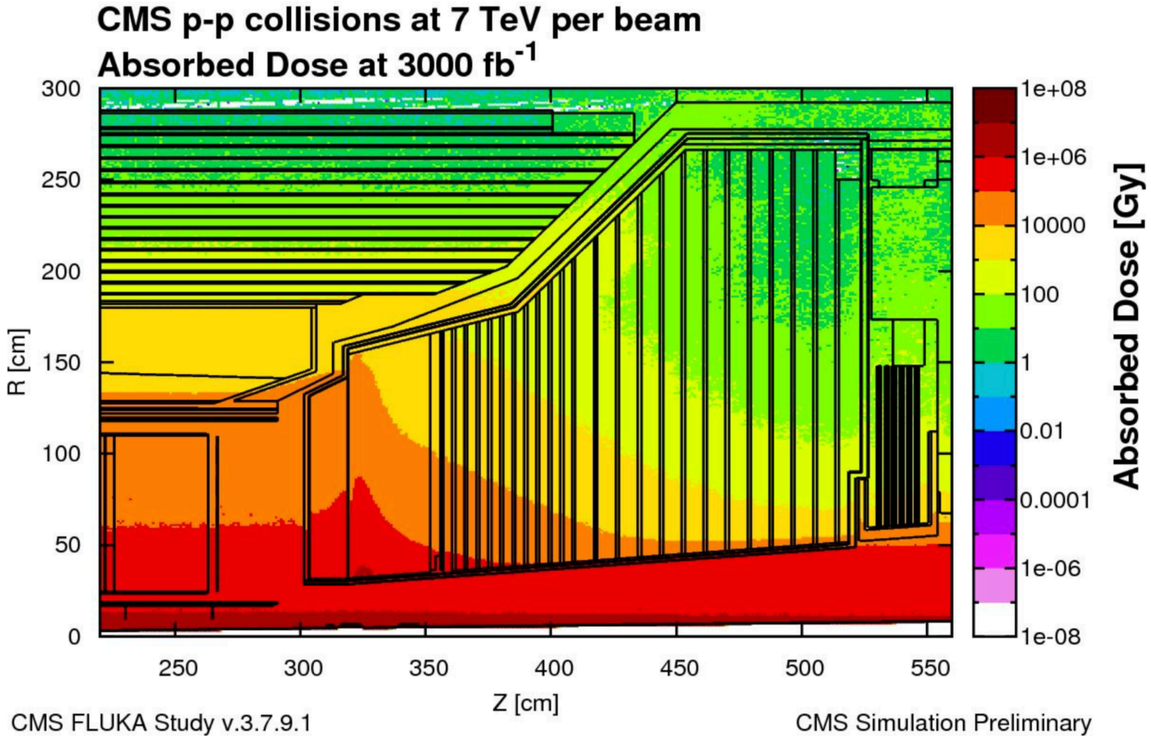
Outline

- Context and motivation
- Fibers layout, composition and characteristics
- Irradiation tests: attenuation and recovery measurements
- Different applications: scintillating fibers vs WLS fibers
- Summary and future development

Motivation

- Need for **radiation-hard** scintillators for applications at colliders
  - **Fused-silica** is a good base material (see CMS HF)
  - **Cerium** as a dopant gives several advantages
    - relatively large LY
    - good overlap between excitation of SiO_2:Ce^{+3} and the emission band of the CeF_3
    - peak emission wavelength appropriate for bialkali PMTs



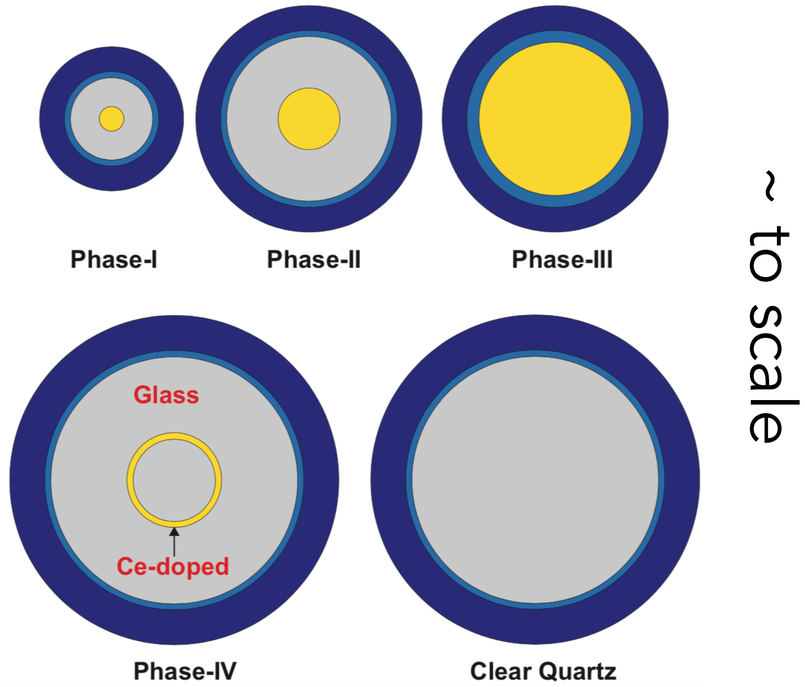
- Doped fibers can be applied either as **scintillators radiators** or as **wavelength shifters** for the collection and transport of light
- The combination of clear and doped fibers opens the door to a **multiple-readout approach**
  - **"Hybrid" fibers: Scintillation and Cherenkov signals in the same fiber**
- Fibers enable the design of detectors with high spatial resolution, good timing properties and their production is cost effective

Fibers layout

Fibers are produced by Polymicro Technologies LLC, Phoenix, AZ

- Composition:
  - Hard-polymer clad + acrylate buffer
  - High OH^- fused synthetic silica

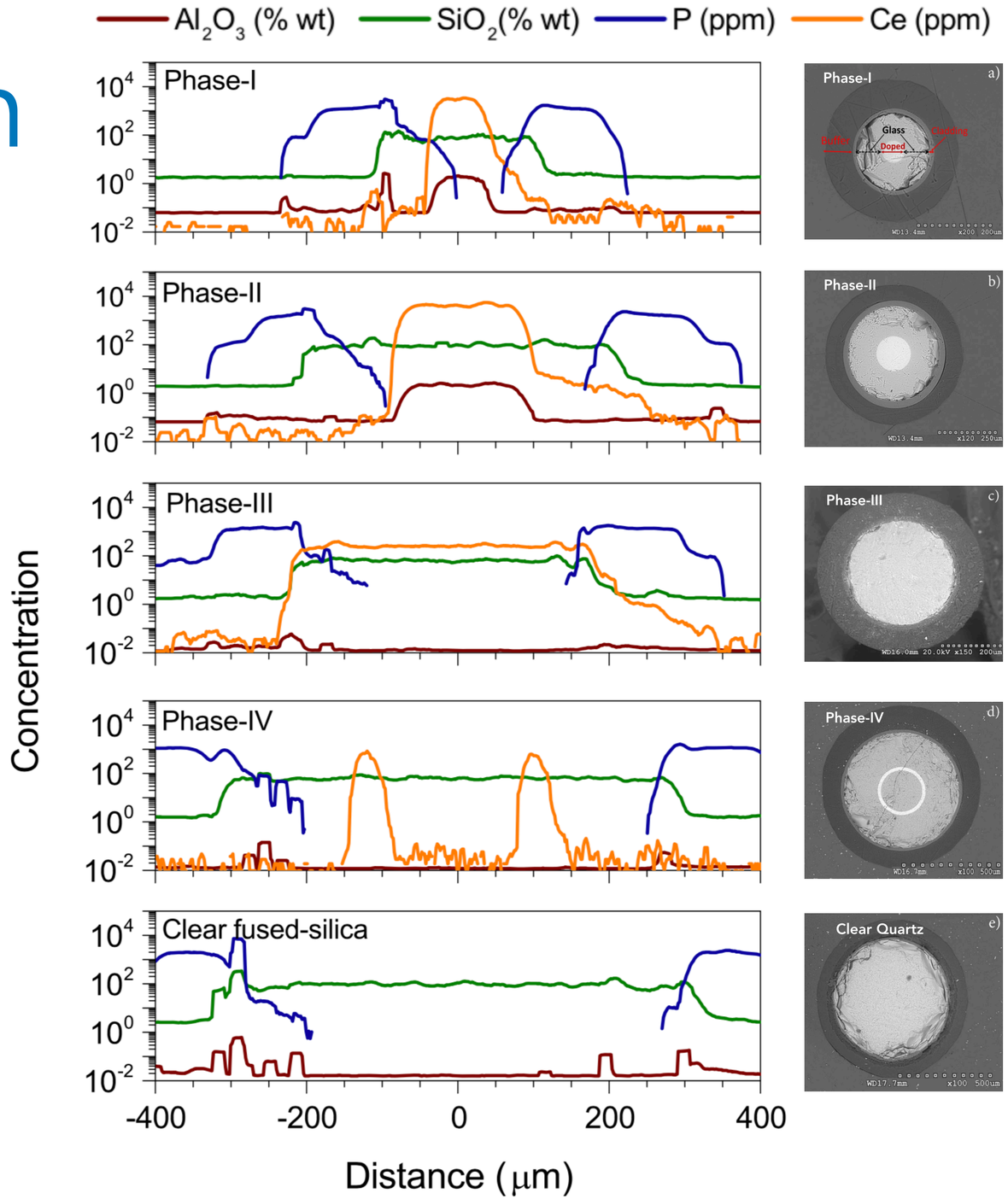
- Different layouts explored to improve radiation hardness and light transmission



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±8(clear) 230±8(doped)	600±6	630±10	800±30
Clear fused-silica	600±10	—	630^{+5}_{-10}	800±30
T14	150±5	400±5	450±5	500±15

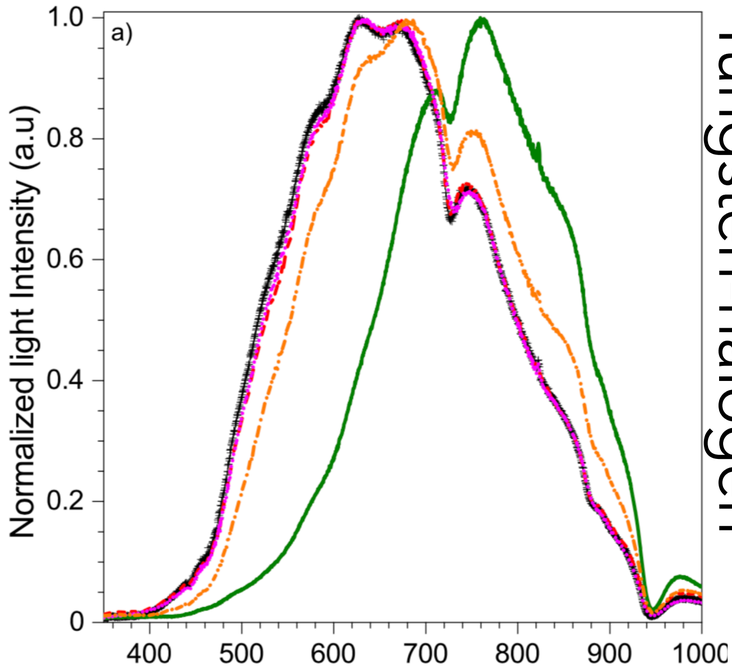
Fibers composition

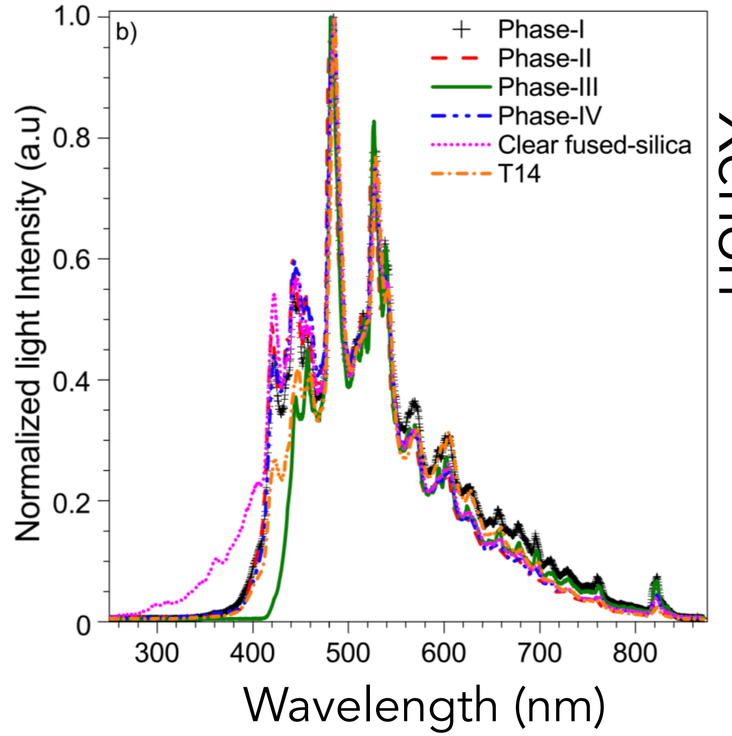
- Mass spectrometer (Agilent 7500cs) used to determine the chemical composition of all fibers
  - Scan rate of 5 µm/s
  - 40-µm diameter laser spot size
- Small concentrations of Ga, La and Gd tend to accompany Ce in glasses
- Significant concentrations of Al in Phase-I, -II
  - Reduced in latest prototypes



Spectral characteristics

- Ce:SiO_2 absorption peak: 329 nm
- Compare transmission of light through 2.5 m of un-irradiated fibers using tungsten-halogen and xenon lamps
  - Reference: **Clear Fiber**
- Observations:
  - Effective light transmission when clear fused-silica component is present (**Phase-I**, **Phase-II**, **Phase-IV**)
  - Absorption of short wavelength particularly evident for **Phase-III**





https://doi.org/10.1088/1748-0221/14/03/P03020

Radiation hardness studies

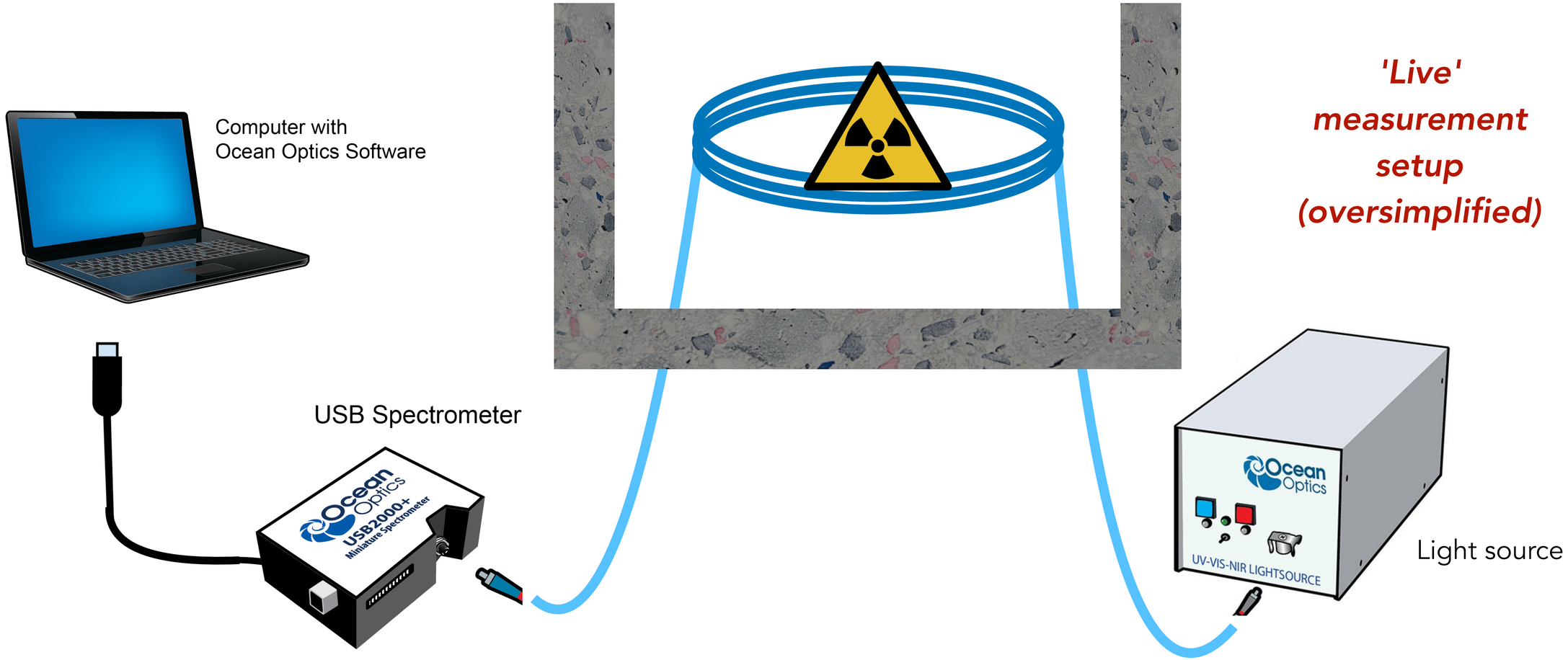
GOAL: study the response after irradiation

- evaluate degradation in photo-luminescence and optical transmission
- model recovery phenomena

Setup

Two irradiation sessions are performed:

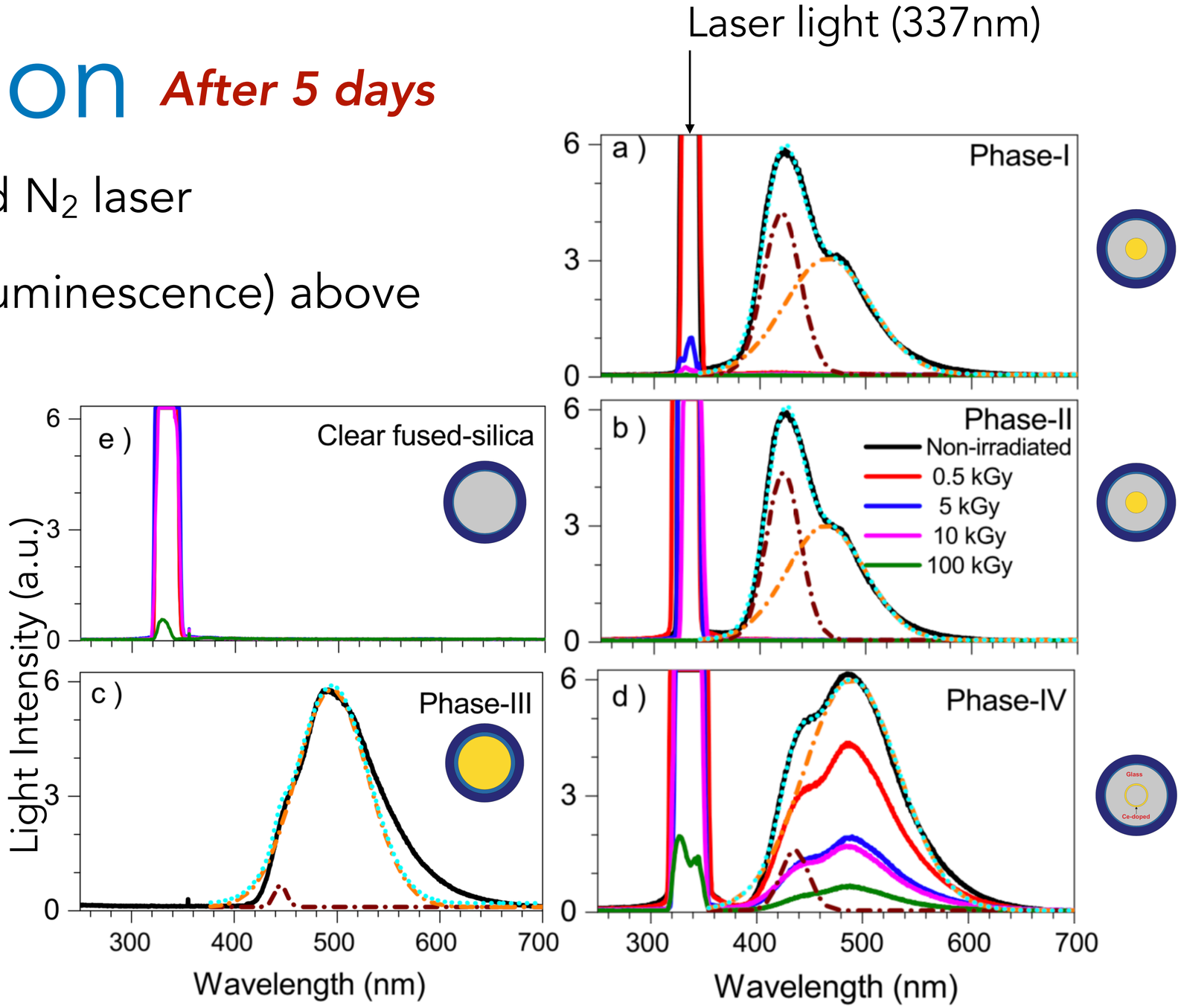
- 0.5, 5, 10, 100 kGy at rates of 0.05, 0.5, 1, 10 kGy/h measure **after 5 days**
- Lower doses, **'live' measurements**



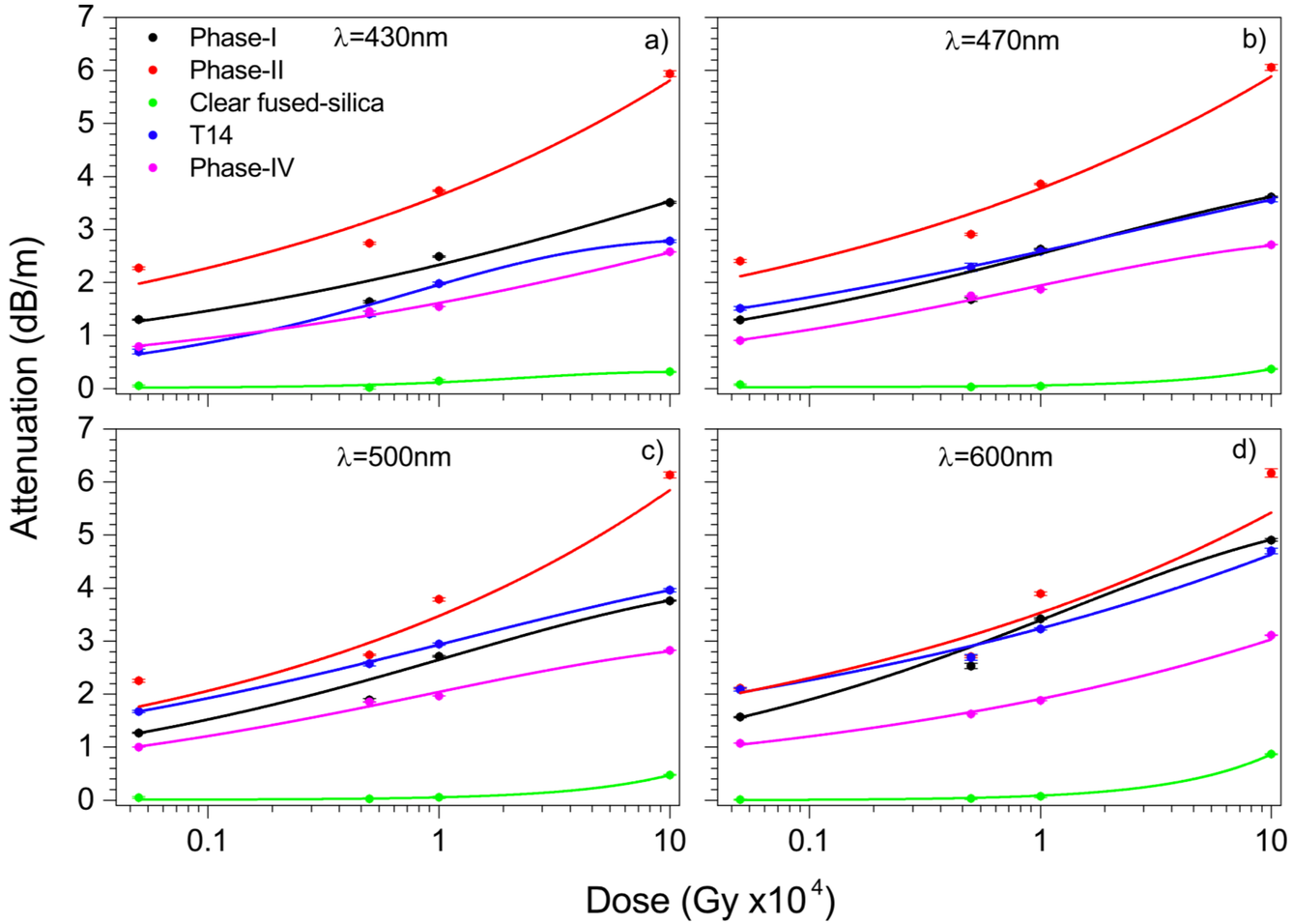
'Live' measurement setup (oversimplified)

Light emission *After 5 days*

- Fibers excited by a pulsed N_2 laser
- Photon emission (photo-luminescence) above 440 nm with a long tail
- Good UV light transmission when clear glass is present
- **Emission still visible for Phase-IV up to 100 kGy**



Light transmission *After 5 days*



- Inject Xenon light axially and measure spectra
  - Four wavelength

- Among the doped fibers, **Phase-IV performs the best**

$$A(\lambda, D) = -\frac{10}{L}\log\left(\frac{I(\lambda, D)}{I_o(\lambda)}\right)$$

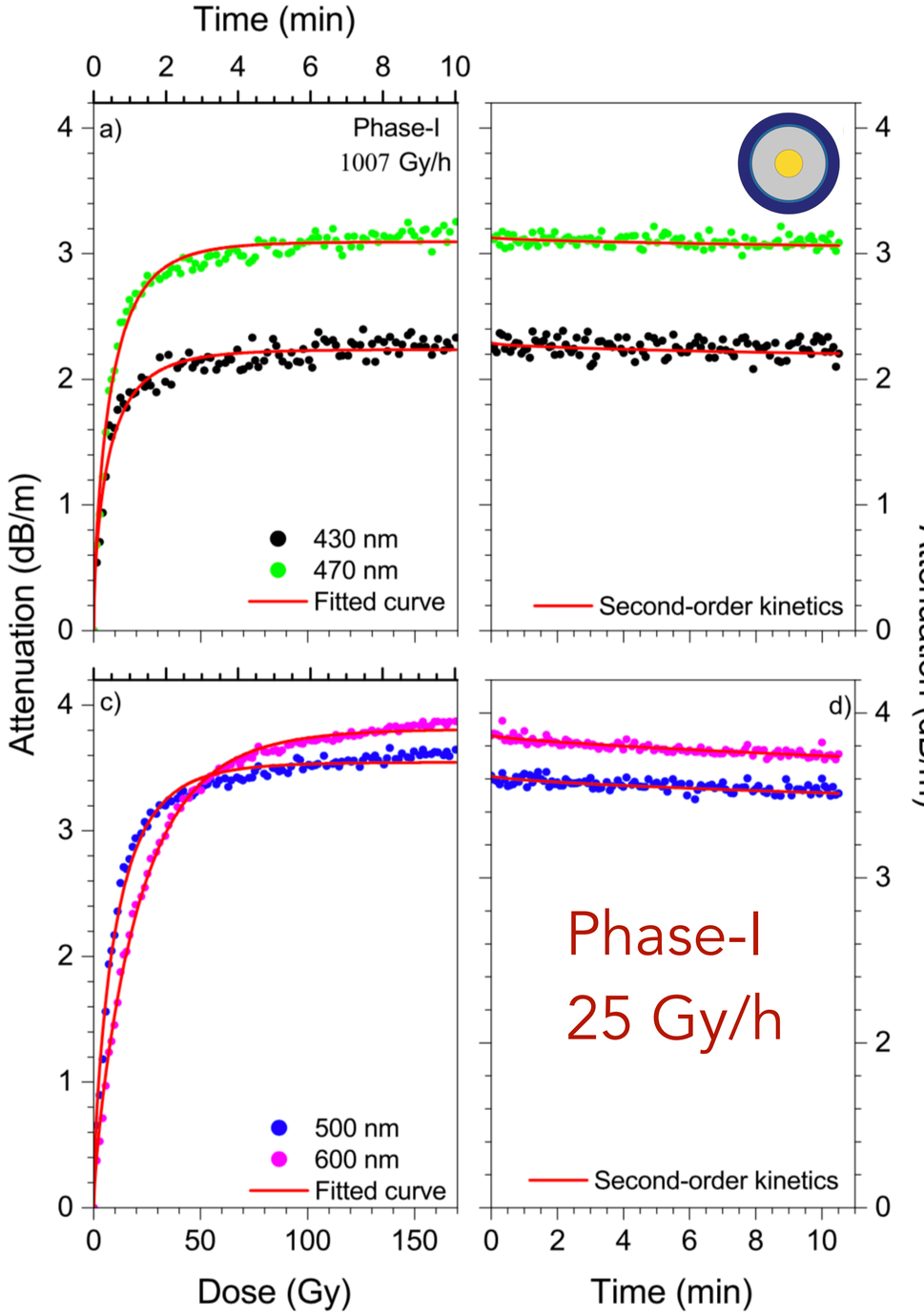
Response evolution **Phase-I**

'Live' meas.

- Attempt to **model rad-induced damage** and optical **recovery**
  - Follow Griscom's classical rate equation with solution

$$N[(kt)^{\beta}] = N_{\mathrm{sat}} \tanh[(kt)^{\beta}]$$

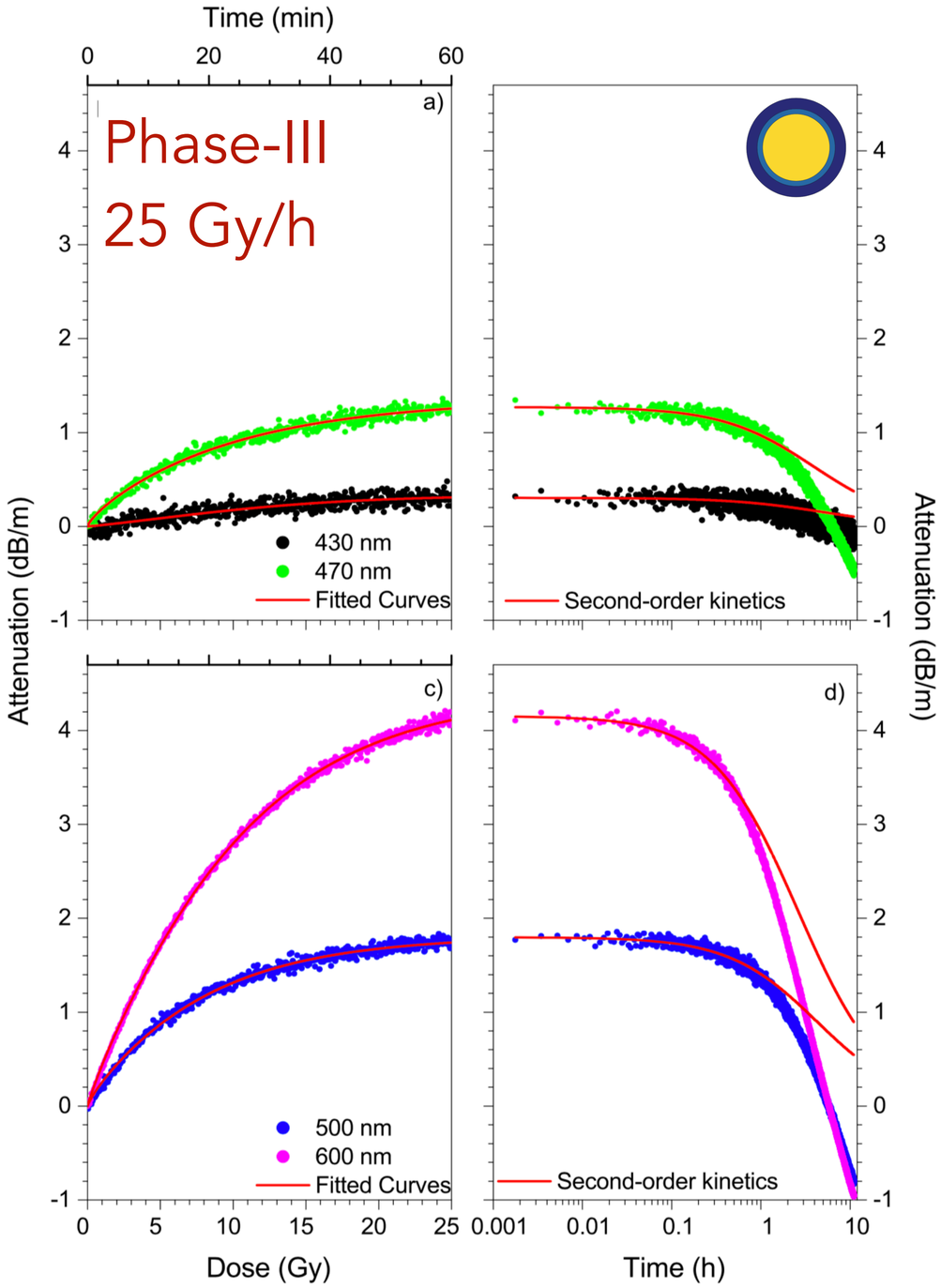
- Fit N_{sat}, k and β during irradiation and extrapolate during recovery
- Main features of damage and recovery are **well described by the fitted model**
  - **Al and P contamination** prevents fast recovery making color centers stable



Response evolution **Phase-III** ***'Live' meas.***

- For Phase-III fibers, the recovery prediction fails to represent the data after an hour of recovery

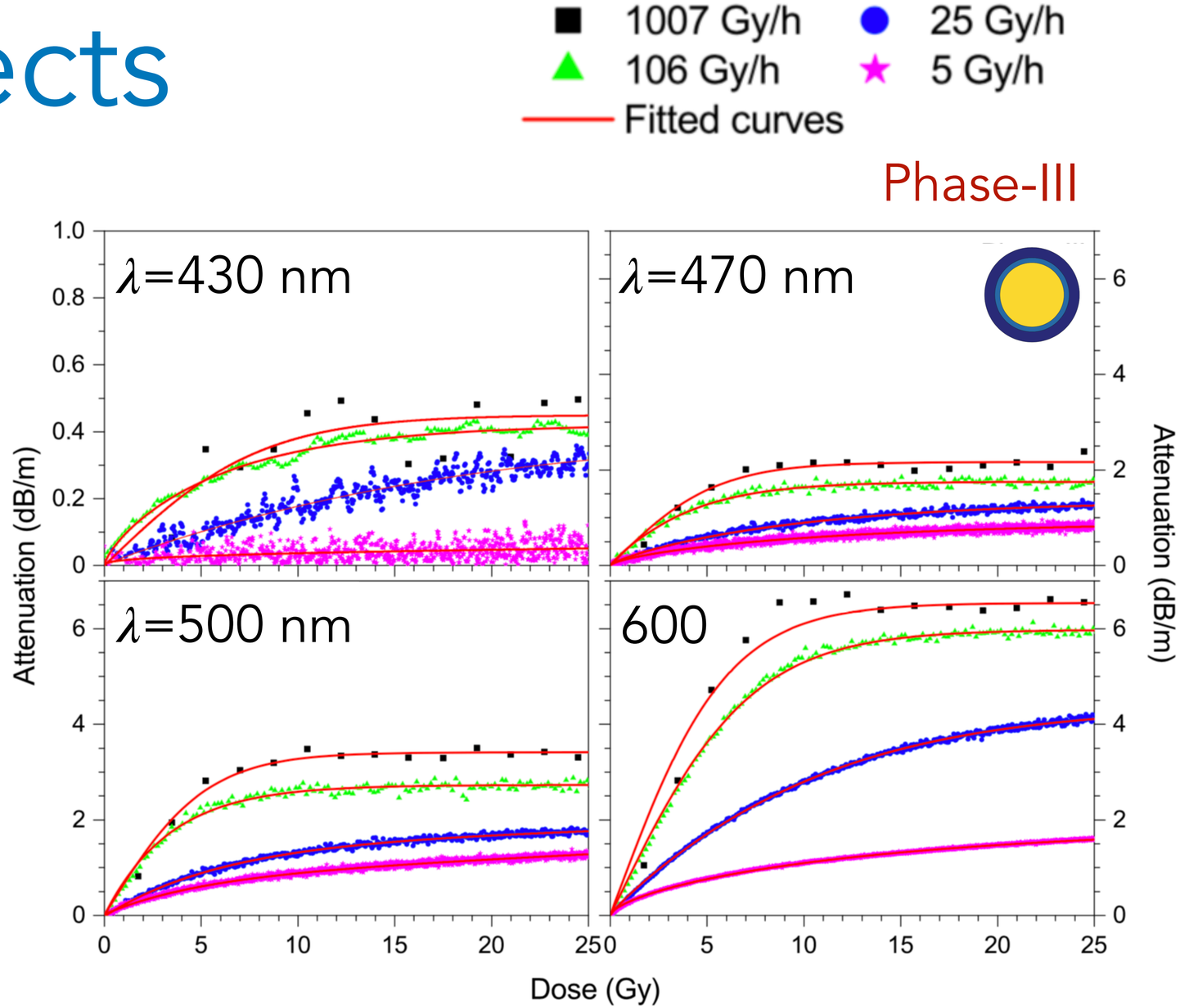
- **Over-recovery** is observed
  - absence of Al and P is likely the responsible of the different behavior wrt Phase-I fibers



Dose-rate effects

- At all wavelengths, the **attenuation increases as a function of dose** and reaches a plateau

- The degree of attenuation at the plateau depends on the wavelength



https://doi.org/10.1088/1748-0221/13/04/P04010

Response to electron beam

GOAL: characterize the response of the fibers

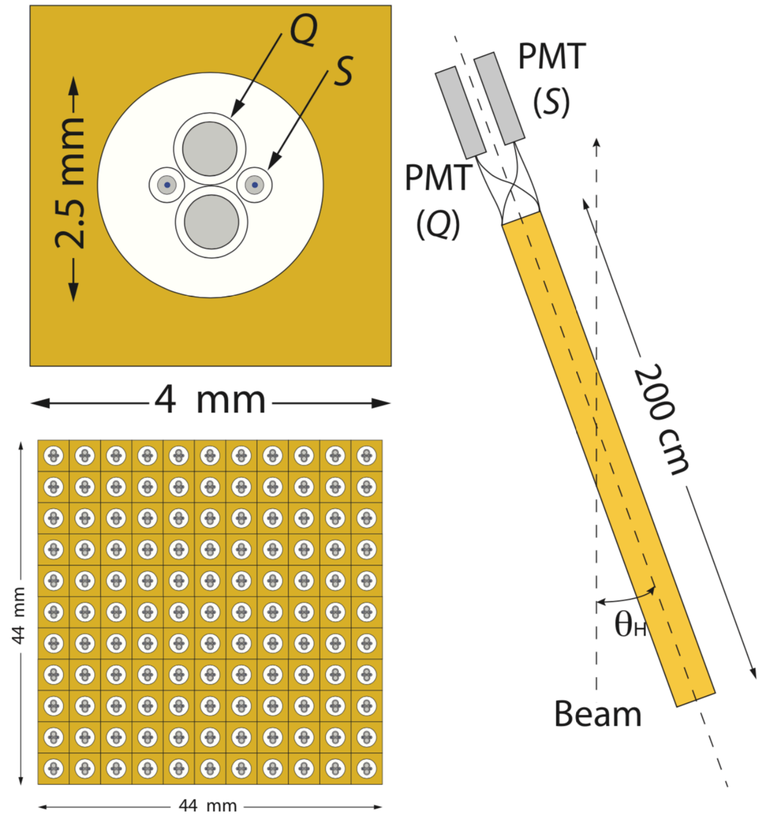
- Pulse shape
- Timing characteristics
- Scintillation light yield

Setup

- A very crude "calorimeter" using Phase-I and clear fibers
  - Phase-I and clear fibers were embedded in a **copper matrix**
  - Transverse size of the matrix: 4.4x4.4 cm^2
  - Length: 200 cm
  - Scint (S) and clear (Q) fibers are **readout separately** by PMT (Hamamatsu R6427)

- This setup was exposed to 4 to 32 GeV positrons at the MTest beamline at Fermilab

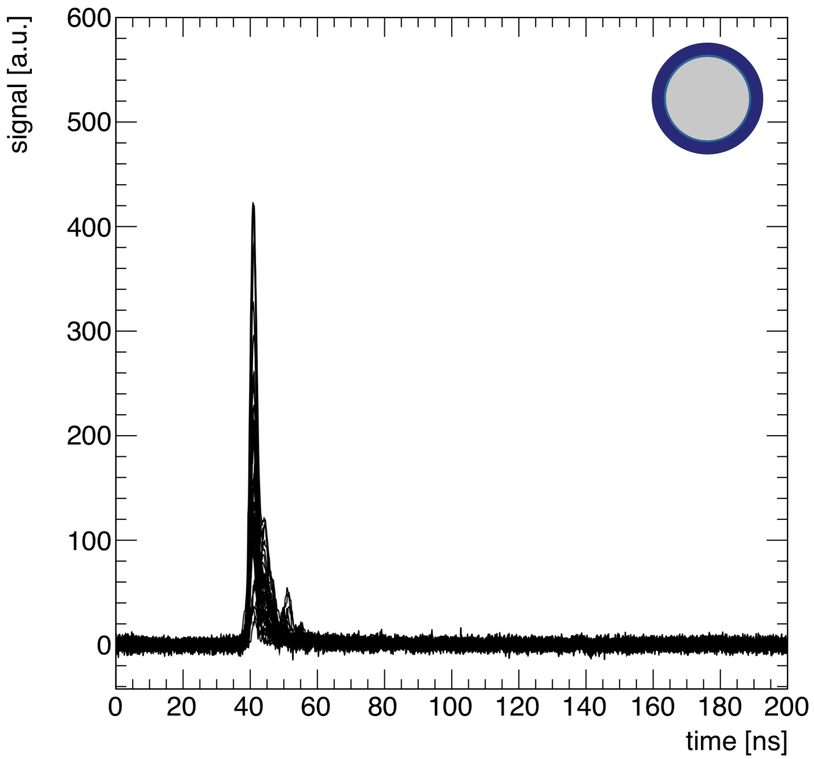
By volume:
- Cu 71.7%
- Air 20.2%
- Clear quartz 3.5%
- Ce-doped core 0.035%
- Glass in Phase-I fiber 0.35%



Signals from 16 GeV positrons

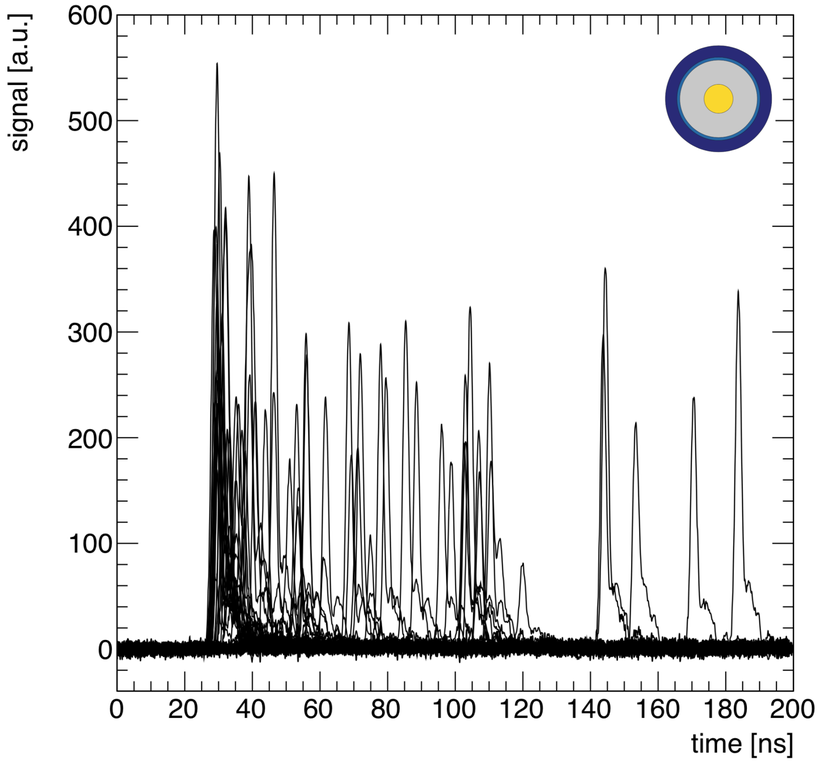
Clear quartz fiber:

- Prompt and fast pulses from Cherenkov



Scintillating Phase-I fiber:

- Both prompt and delayed signals
- Most pulses correspond to single p.e.



Pulse shape

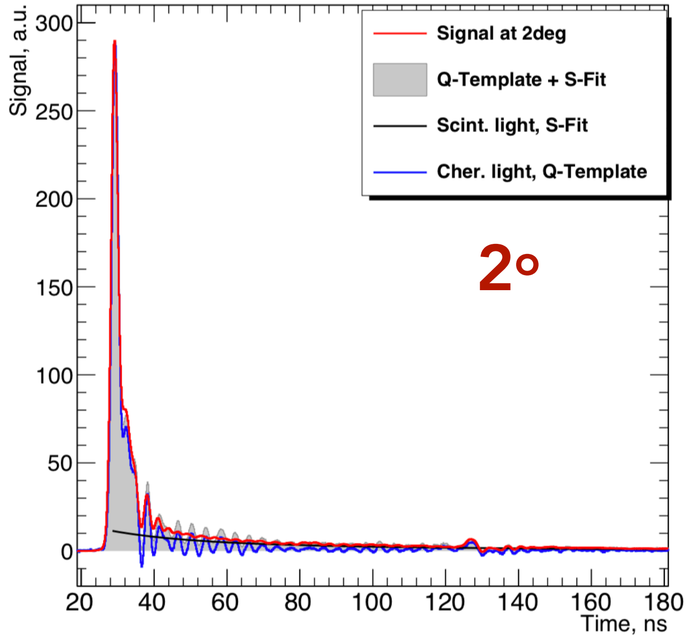
- Can control the abundance of Cherenkov light by changing the orientation of the fibers wrt beam
  - Cherenkov: **directional**
  - Scintillation: **isotropic**

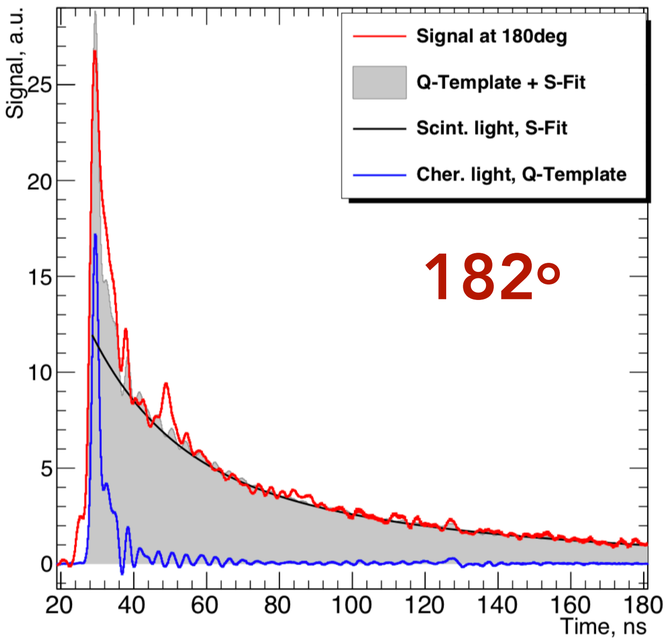
- The scintillation contribution has **two components**:

$$S(t) = a_1 e^{-\frac{t}{\tau_1}} + a_2 e^{-\frac{t}{\tau_2}}$$

  - Fast: τ_1 = 20.8 ± 5.4 ns (23.9±5.3%)
  - Slow: τ_2 = 93.0±12.6 ns (76.1±5.3%)

- **Absolute Light yield** was measured to be between 500 and 700 γ/MeV depending on the fiber's type

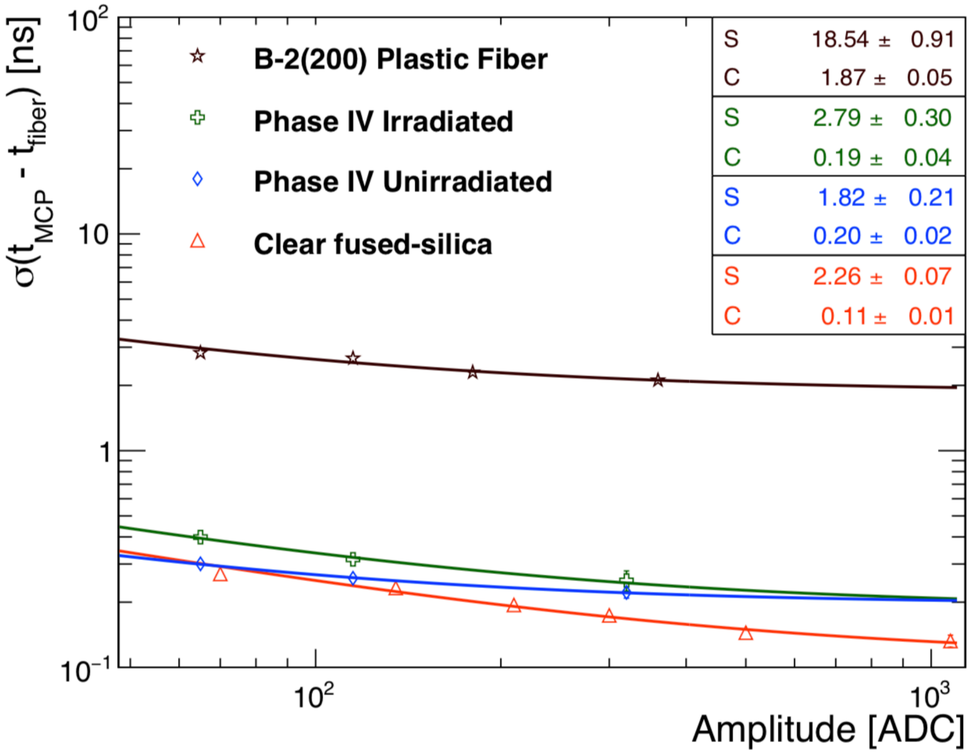




Timing measurements

- The prompt Cherenkov signal **could be exploited for timing applications**
- Using a fast MCP as time reference it is possible to measure and compare the time resolution for different fibers
  - Better performance when comparing to scintillation signal (expected)
  - Degraded performance for the irradiated sample due to a worsening of the light transmission
- Precise measurement should be performed with a dedicated setup

$$\sigma_t^2 = \left(\frac{s}{\sqrt{A}}\right)^2 + c^2$$



https://doi.org/10.1088/1748-0221/14/06/T06006

Fibers as wavelength shifters

GOAL: evaluate fiber's performance when coupled to a scintillating crystal

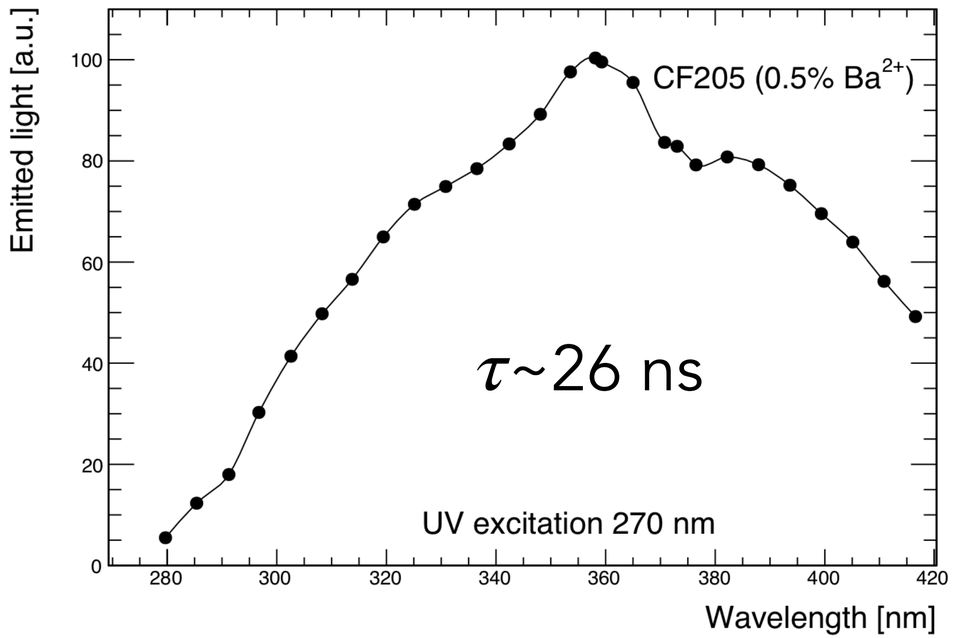
- Pulse shape
- Collection efficiency
- Evolution of response after irradiation

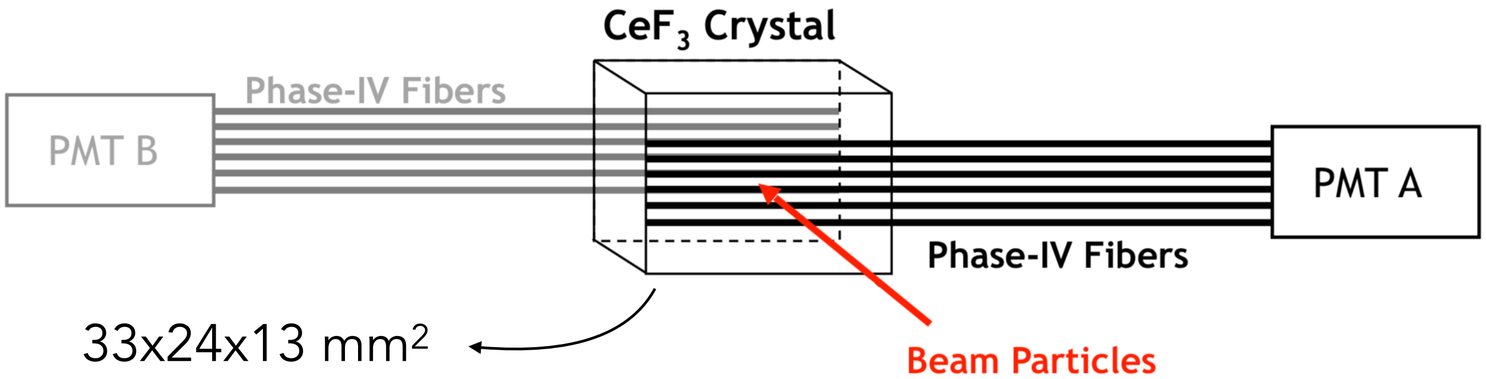
Couple fibers with CeF_3 crystal

- Two sets of Phase-IV fibers are coupled to a CeF_3 crystal
  - New vs irradiated (100 kGy) bundle

- Substantial overlap between the excitation of the $SiO_2:Ce^{+3}$ and the emission band of the CeF_3

CeF_3 emission spectrum





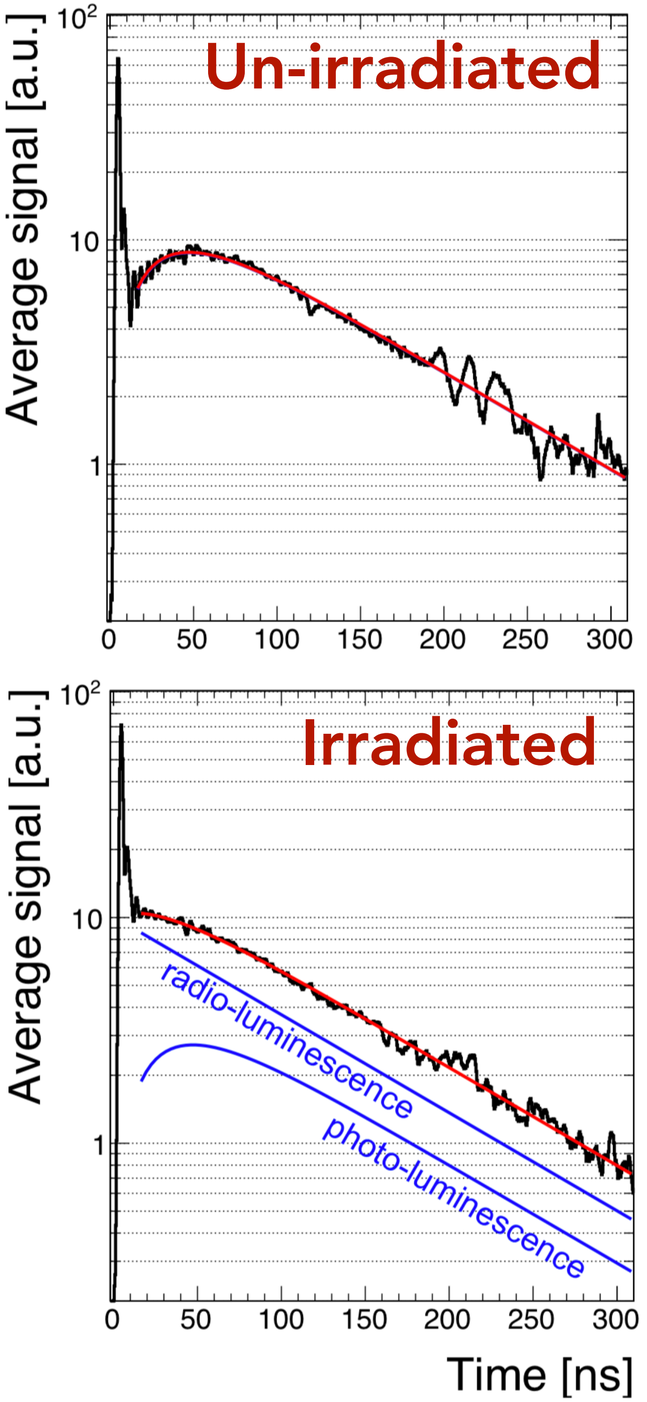
Abs peak: 329 nm	RM = 2.6 cm
ρ = 6.16 g/cm^3	λ_I = 25.9 cm
X_o = 1.68 cm	n = 1.68

Compare irradiated vs un-irradiated

- **Two components** of the signal:
  - direct excitation of the fibers (**radio-luminescence**)
  - light from the crystal that excites the fibers (**photo-luminescence**)

- Model the signal shape analytically (**different time charact.**)
  - Un-irradiated fiber is best described with a ~100% contribution from the photo-luminescence
  - Irradiated fiber suggests that only 1/4 of the total signal comes from photo-luminescence

- Possible explanations:
  - loss of performance for both emission and transmission
  - reduced transmission of the scintillation light from cerium fluoride through the cladding of the fiber



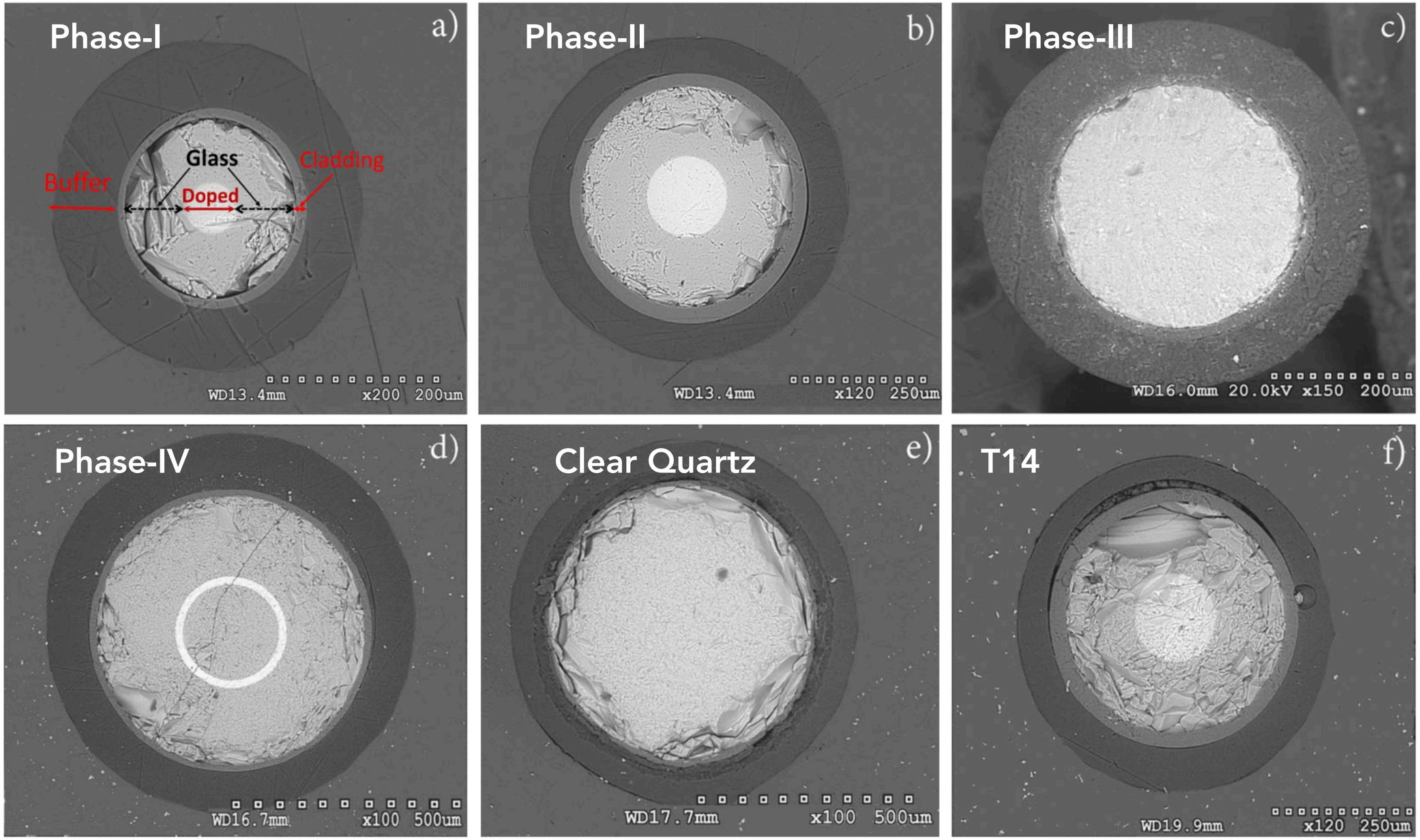
Summary and next steps

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

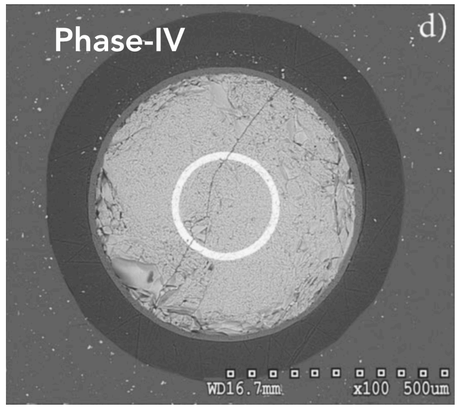
- Hybrid fiber structure ("clear"+"doped") may prove useful in some detector applications in HEP

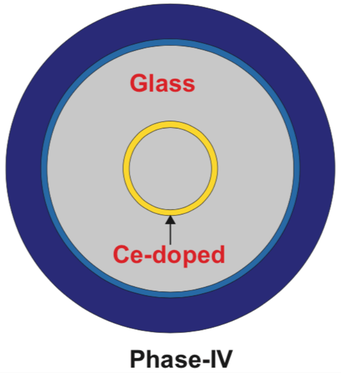
- Attention is paid to reproducibly manufacture fibers in an industrial setting
- Phase-V fibers are currently under development

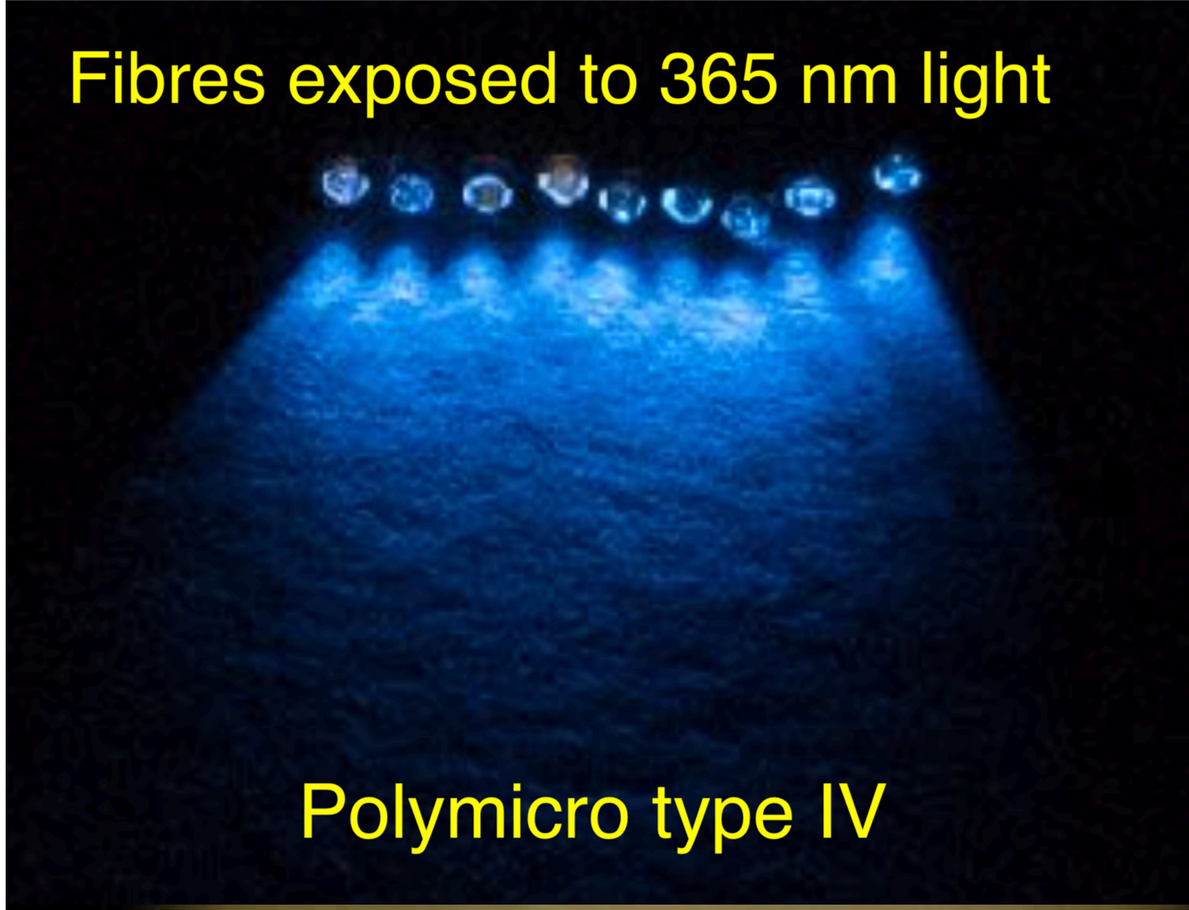
Backup


Phase-I
a)
Glass
Cladding
Buffer
Doped
WD13.4mm x200 200um
Phase-II
b)
WD13.4mm x120 250um
Phase-III
c)
WD16.0mm 20.0kV x150 200um
Phase-IV
d)
WD16.7mm x100 500um
Clear Quartz
e)
WD17.7mm x100 500um
T14
f)
WD19.9mm x120 250um

Phase-IV


Phase-IV
d)
WD16.7mm
x100 500um


Glass
Ce-doped
Phase-IV

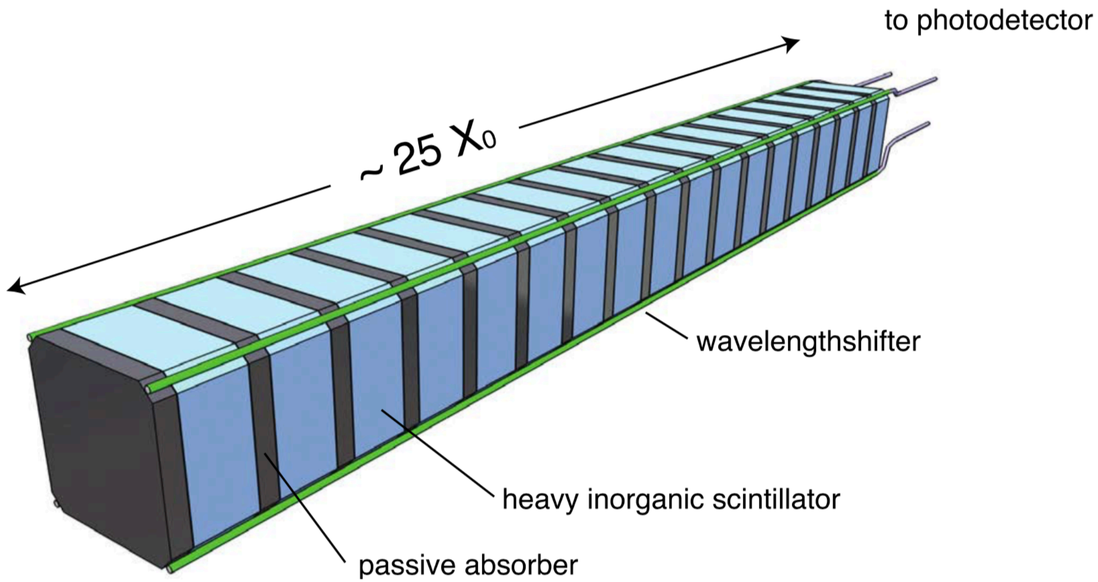

Fibres exposed to 365 nm light
Polymicro type IV

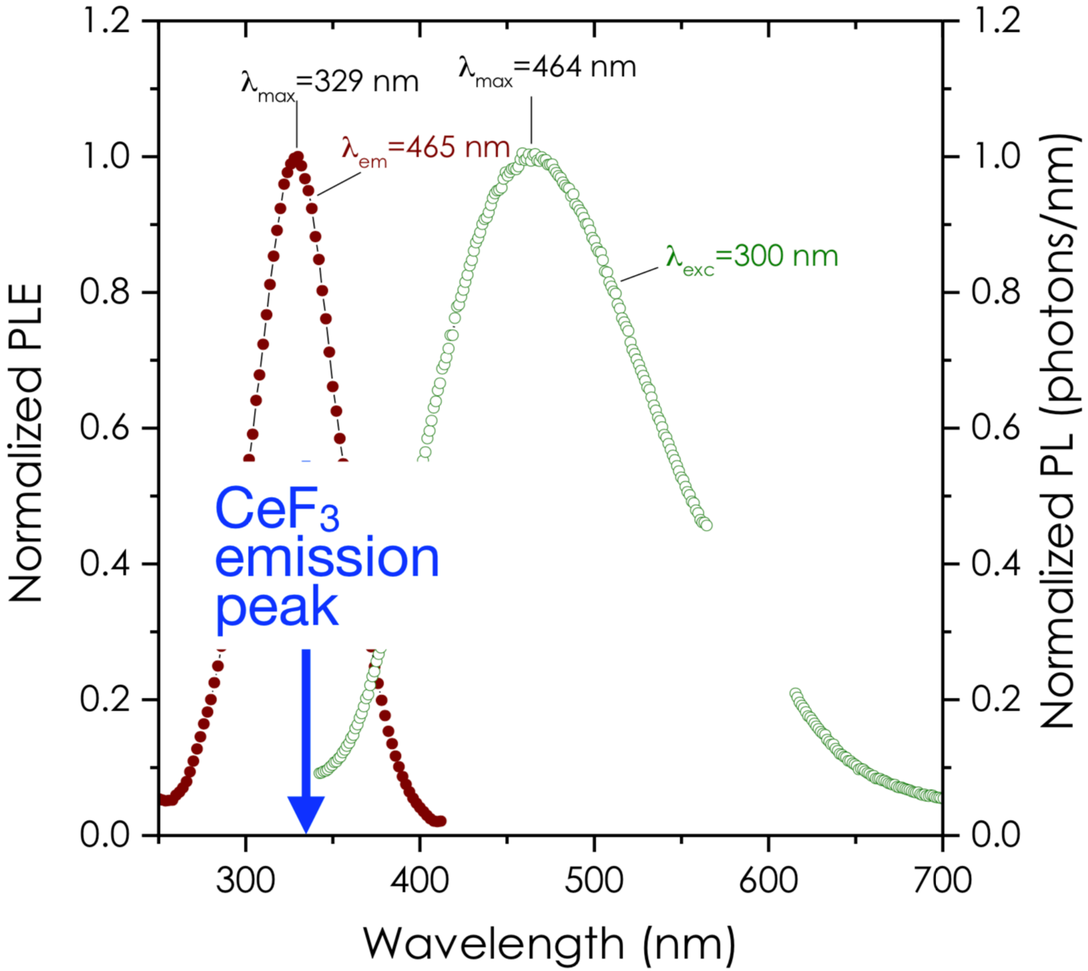

Visible light through fibers

Tungsten CeF_3 array prototype

Francesca Nessi et al

TIPP2017





Rad-damage and optical recovery modeling

We follow Griscom's classical rate equation for second-order growth with thermally activated decay approach [34]:

$$dN(t)/dt = K\dot{D}N^* - RN^2/N^* \tag{4.4}$$

with its solution

$$N(t) = N_{\text{sat}} \tanh(kt) \tag{4.5}$$

where $N_{\text{sat}} = (K\dot{D}/R)^{1/2}N^*$ and $k = (K\dot{D}R)^{1/2}$. N stands for the number density of color centers, $R = 1/\tau$ is the decay rate constant, K governs the creation of new color centers, N^* has the dimensionality of the color center number density. The "stretched" version of the second-order growth kinetics is accomplished by the $kt \rightarrow (kt)^{\beta}$ substitution where kt is dimensionless.

$$dN[(kt)^{\beta}]/d(kt)^{\beta} = (K\dot{D}/R)^{\beta/2}N^* - (R/K\dot{D})^{\beta/2}N^2/N^* \tag{4.6}$$

with $0 < \beta < 1$ and $k = (K\dot{D}R)^{1/2}$. The solution is

$$N[(kt)^{\beta}] = N_{\text{sat}} \tanh[(kt)^{\beta}]. \tag{4.7}$$

Here, $N_{\text{sat}} = (K\dot{D}/R)N^*$ and $k = (K\dot{D}R)^{1/2}$. The classical time-independent rate constant K and β are determined by fitting the experimental data. The recovery in this system of equations is

$$dN[(Rt)^{\beta}]/d(Rt)^{\beta} = -N^2/N^* \tag{4.8}$$

with solution

$$N[(Rt)^{\beta}] = N(0)\{1 + [N(0)/N^*](Rt)^{\beta}\}^{-1}. \tag{4.9}$$

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)