Radiation damage to LHC fibres

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Overview

- Introduction
- Doped a-SiO_2
- Attenuation of light
- Kinetic modeling
- Experimental results
- Conclusion

Introduction

- Electronics will be installed in the tunnel close to beam
  - optimise performance
  - increase the S/N ratio
  - reduce cabling costs

- Data is mainly transmitted via a fieldbus protocol to surface buildings
  - copper
  - optical fibre

- 3 major distributed communication systems use fibre optical links
  - Quench Protection System
  - Power Converters
  - Cryogenics system

- Another big consumer of fibres is the BLM/BPM system
  - transmits raw data from BPMs/BLMs crates over fibre optical to surface.

- Fibres in the LHC tunnel will suffer from radiation-induced attenuation
  - may eventually halt the communication of data after a few years of operation
  - radiation-induced attenuation depends on the type and the concentration of dopants Phosphor (P), Fluorine (F), Germanium (Ge) in the amorphous silicon dioxide (a-SiO2) core
  - at present Ge-P-doped and Ge-doped fibres are being installed in the LHC tunnel.

Doped a-SiO_2

- a-SiO_2 is a material with **unordered silicon atoms**
  - dangling bonds
  - distorted Si-Si bonds

- Defects yield intermediate energy levels in the energy gap
  - incident light excites electrons from valence band to intermediate energy levels
  - trapped electron in a potential well and acts as an oscillator (absorber of light)
  - limits transmission in pure a-SiO_2

- a-SiO_2 fibre doped with impurities (Ge,P,F)
  - adding impurities to the a-SiO_2 structure changes the energy structure

- a-SiO_2 deposited under hydrogenation (Plasma Chemical Vapour Deposition)
  - hydrogen atoms saturate dangling and weak bonds
  - removes defects and creates a defect-free energy gap
  - excited electrons do not have enough energy to bridge the energy gap
  - the absorption of light in the fibre is strongly reduced

- Fibres in the LHC tunnel
  - Ge-P doped a-SiO_2 from Draka NK Cables Ltd
  - Ge doped a-SiO_2 from Draka Fibre Technology BV (PCVD process)

Attenuation of light

- The attenuation of an optical link depends on the wavelength of light
  - three low-loss windows of interest
    - 850 nm widely used with multimode (MM) fibres (850 nm LEDs are inexpensive)
    - 1310 window offers **lower loss** but at modest increase in the cost of the LEDs ← used at CERN
    - 1550 nm window is mainly of interest in long distance telecommunications applications
- Absorption spikes
  - exist if SiO_2 contains impurities/point defects
  - are created if the sample is exposed to radiation
    - radiation can **activate** pre-existing point defects
    - radiation can **create** totally new point defects
- Wavelength at which the defects absorb
  - depends on the structure of the point defect
  - depends on the type of dopant involved
- SM LHC fibres have attenuation of approximately 0.35 dB/km at 1310 nm
  - optical joints and connectors add to this
    - LHC connectors inspected with an interferometer: 1 dB per optical connection guaranteed
  - radiation damage adds to this
    - we **must assess** how much

Defect creation

- Creation of point defects by radiation (knock-on and radiolysis)
  - the knock-on process
    - direct transfer of the projectile kinetic energy **causes atomic displacements**
    - may create an interstitial-vacancy (Frenkel) pair or a site distortion
    - produced by fast/thermal n^0, energetic ions, energetic e^- and γ rays (indirectly)

  - the radiolysis process
    - radiation **changes the state** of an electron
    - energy absorbed appears as
      - 'hot' electrons (in a normally empty conduction band)
      - 'hot' holes (in a normally occupied valance band)
      - excitons (electron-hole pairs bound to each other)
    - localization at suitable lattice sites (traps)
    - leads to stable electronic states (creation of colour-centres)

Kinetic modeling (I)

- The dependence of the population on **dose rate** (and temperature)
  - easily seen in a simple, first order kinetic formulations

$$\frac{\partial n}{\partial t} = a\dot{D} - \frac{n}{\tau}$$

n = defect concentration
D = dose-rate
a = probability of defect generation
τ = characteristic defect lifetime

- Isothermal, constant dose-rate regime
  - solution is a **saturating exponential**

$$n = a\dot{D}\tau\left[1 - \exp\left(-t/\tau\right)\right]$$

- Transformation to a dose-equivalent formulation
  - assume saturating dose, D_s = dose rate × characteristic lifetime

$$D_s = \dot{D}\tau$$

Kinetic modeling (II)

- Kyoto considers **sum** of saturating exponentials

$$A(t)=\sum_{i=1}^{n-1}\left[k_i\left(1-\exp\left(-t/\tau_i\right)\right)\right]$$

- K1,2…n-1 correspond to **saturation** values of different contributions (dependent on the dose rate)

$$K_i=K_i\left(\dot{D}\right)$$

- Radiolysis attenuation **anneals** when irradiation stopped. Recovery is parameterised as

$$A(t)=\sum_{j=1}^{m-1}\left[A_j\exp\left(-t/\tau_j\right)\right]$$

- The characteristic lifetime τ can vary in magnitude from **minutes** to **infinity**

Kinetic modeling (III)

- Reasonable to assume the number of defects is **proportional** to absorbed dose

$$A(t) = K_n \quad , \quad K_n = K_n(D)$$

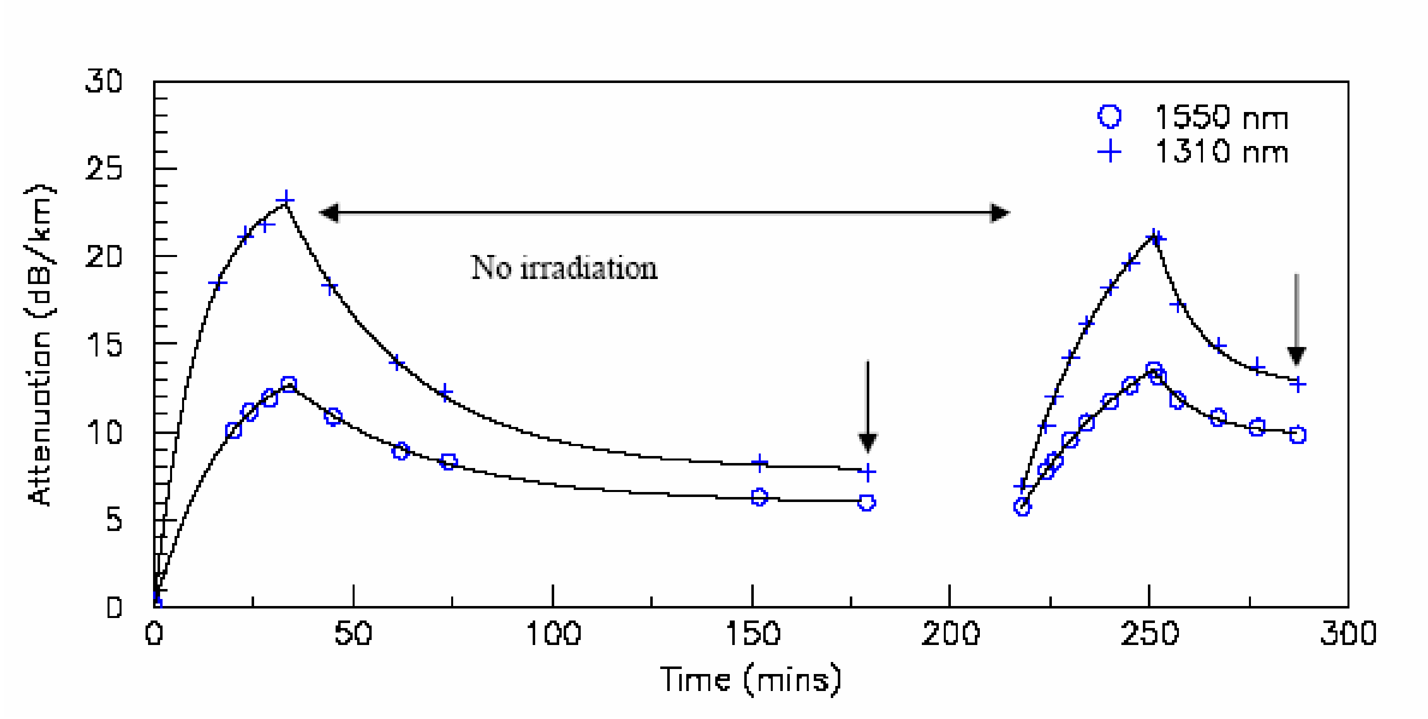
- Validity range limited by saturation at very high doses and transients during intense, pulsed irradiation

After a sufficiently long shutdown period, the attenuation in a LHC fibre in the tunnel will be almost entirely determined by the value of the total accumulated dose

Results (I)

^{60}Co at POSEIDON, CEA-Saclay 1000 Gy/hr

Ge doped SM fibre (Draka Fibre Technology BV)



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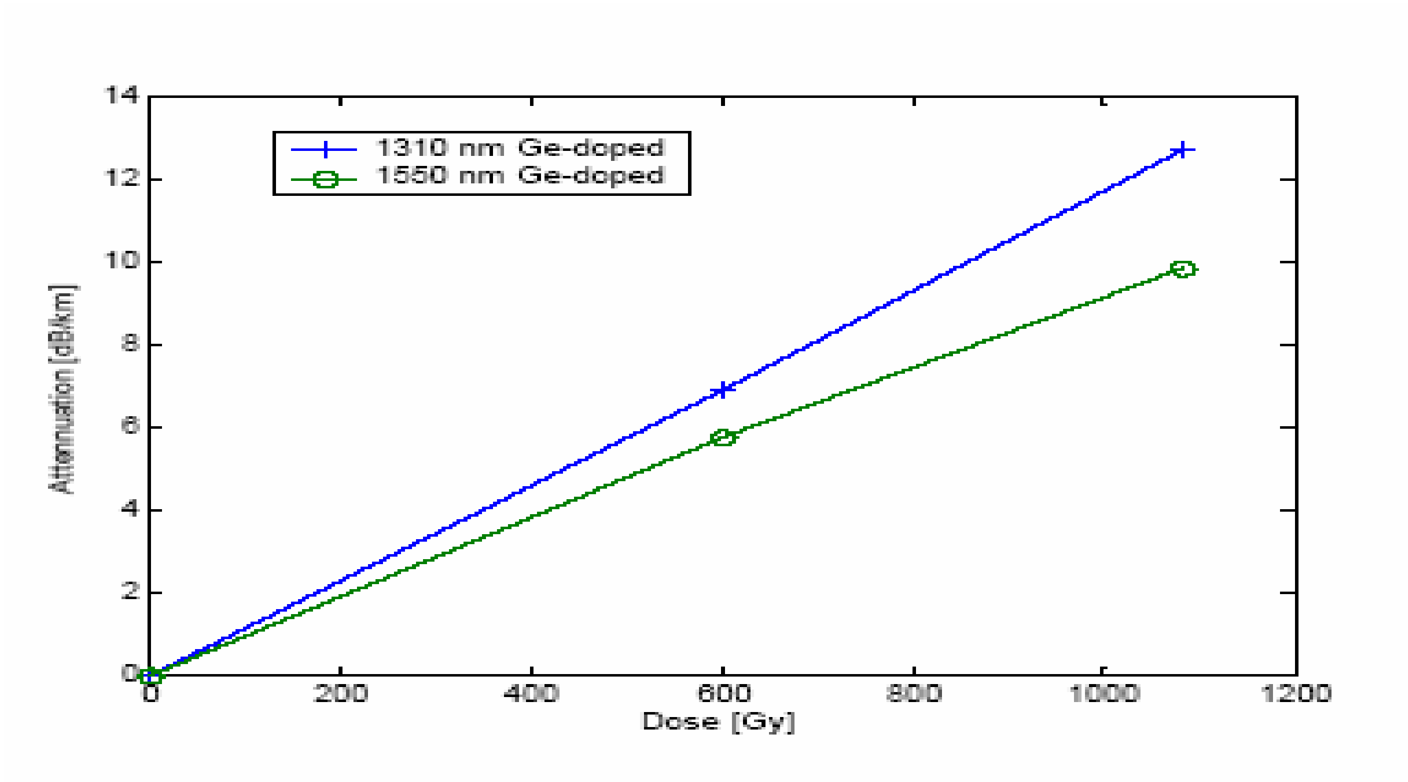

Results (III)

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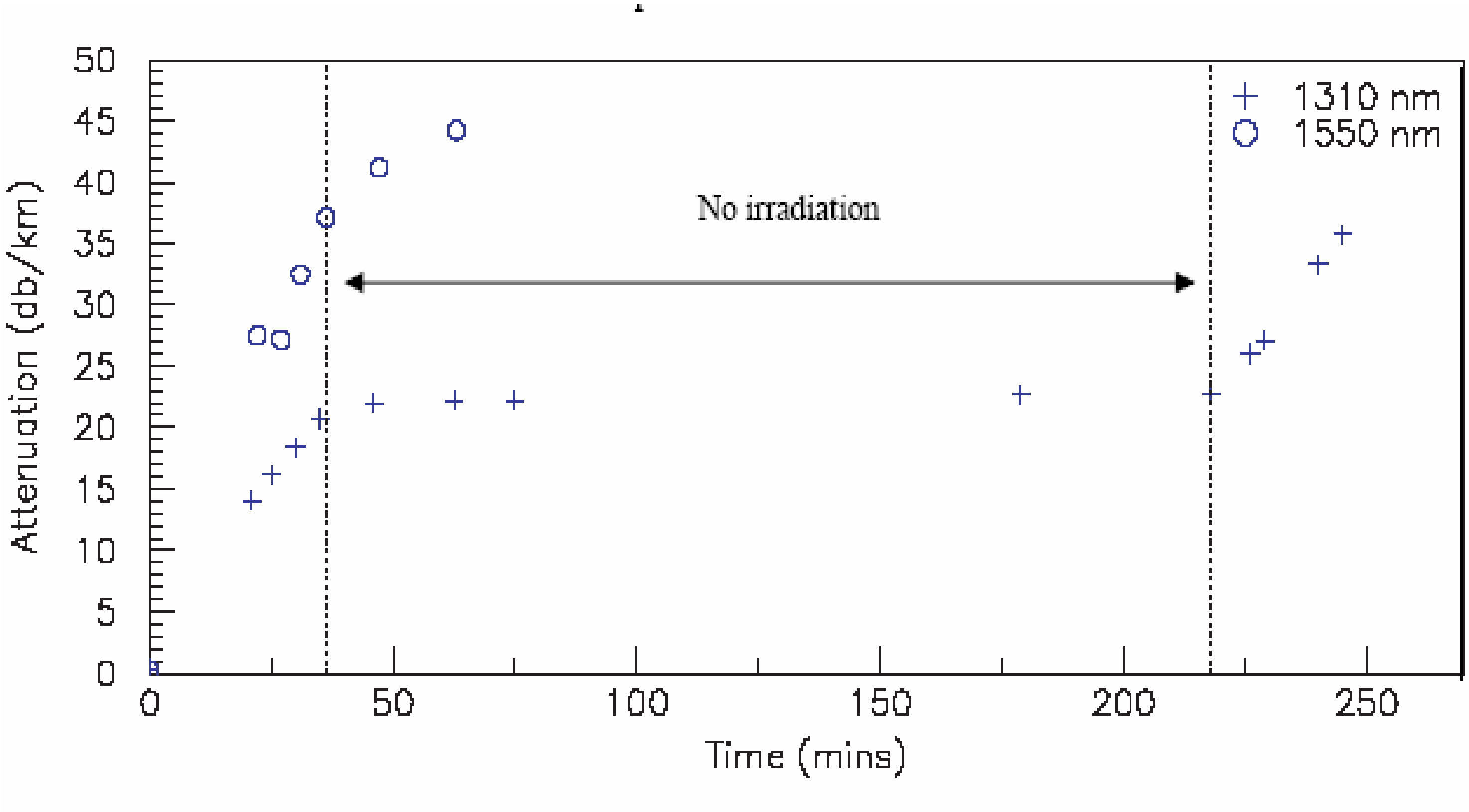

Fit to kinetic models

- Ge-doped fibres at 1 kGy/hr
  - dynamic response
    - single, dose-rate dependant, saturating exponential
  - permanent damage
    - remains after annealing period
    - linear dependence on total dose

fit coefficients	1310 nm	1550 nm
K_1[dB/km]	24.20	14.50
τ_1[mins]	11.16	17.40

Table I. Fitting parameters for the radiation-induced attenuation in Ge doped fibres

- Ge-P-doped fibre at 500 Gy/hr
  - dynamic response
    - no evidence of saturation
  - Permanent damage
    - no evidence of annealing
    - single dose dependent term
  - consistent with literature
    - attributed to P1 defect (1570 nm)

fit coefficients	1310 nm	1550 nm
A_1[dB/Gy.km]	15.34	6.75
τ_1[mins]	31.14	35.93

Table II. Fitting parameters for annealing at of the radiation induced attenuation in Ge-P doped fibres

Extrapolation to LHC

- optical fibre path
  - from electronics crate under a cryostat at mid ARC
  - to an acquisition crate in the control room at SR7

- radiation source
  - beam-gas interaction in the ARC
  - point losses in DS and LSS (collimator location)

- working assumptions
  - radiation levels from Mars and Fluka simulation
  - 200 days LHC operation per year

Extrapolation to LHC

Tunnel area	**Distance [m]**	**Dose rate [Gy/h]**	**Annual Dose [Gy]**	**Attenuation [dB/y]** **1310 nm Ge-P**	**Attenuation [dB/y]** **1310 nm Ge**
LSS R7	270	0.625	3000	64.8	8.1
DS R7	170	0.002	10	0.14	0.02
Half Arc	1214	0.001	5	0.49	0.06
Total	1654	-	3015	65.4	8.1

Conclusion

- Increase in the attenuation at 1310 nm due to radiation damage

- Attenuation will depend on
  - type and concentration of dopants
  - accumulated dose
  - dose rate

- Attenuation in Ge-P-doped 0.08 dB/km per Gy at 1310 nm
  - dose rate of 500 Gy/hr
  - 8 times higher than Ge-doped
  - increases linearly with accumulated dose
  - no saturation observed
  - no annealing observed
    - possibly it is not observable on considered timescale