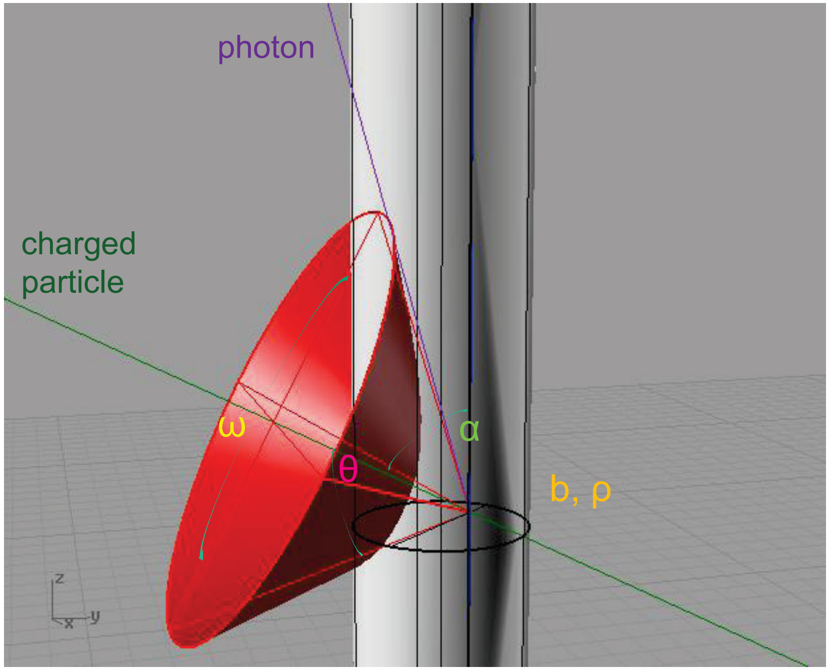
Fiber Based BLM System R&D at CERN –

Quantitative loss measurement with long bunch trains



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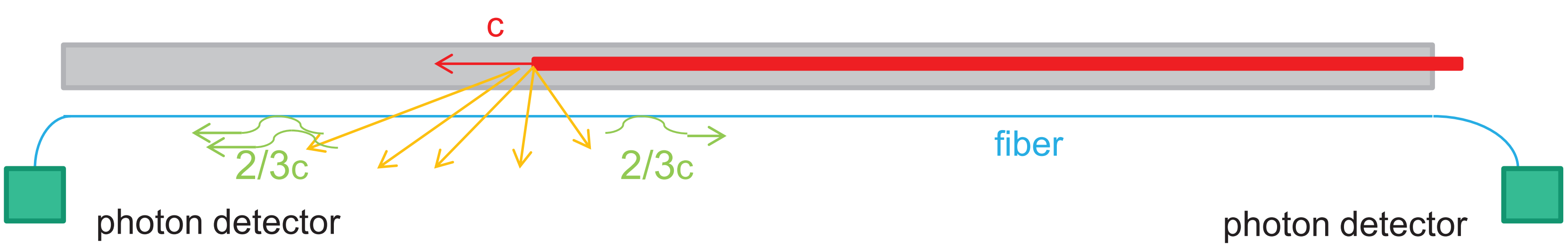
52nd ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams
Beijing, China

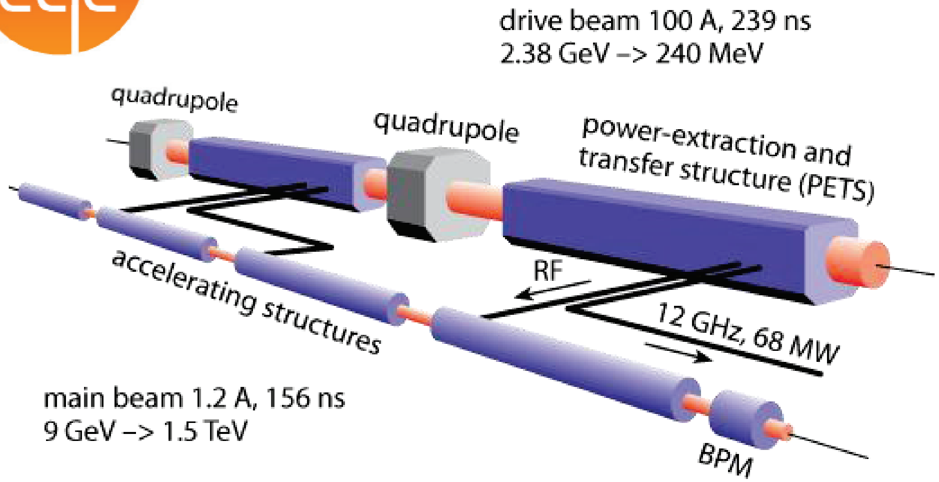
Outline

- Motivation
- Cherenkov Fiber BLMs
  - Modeling and FLUKA Simulations for CLIC Drive Beam
  - Sensitivity and Dynamic Range
  - Radiation Hardness and Attenuation
- Longitudinal Resolution
- Summary and Outlook



Motivation

The CLIC (Compact Linear Collider) Two-Beam-Module



- Future e+/e- collider, centre of mass energy of 3 TeV
- Accelerated from 9–1500 GeV in 21 km
- High accelerating gradients (100 MV/m) → novel two beam acceleration method
- High intensity Drive Beam decelerated in Power-Extraction and Transfer Structures (PETS)
- RF power at 12 GHz is transferred to the Main Beam

	Energy range (GeV)	Rep. rate	**Pulse length**	Bunch frequency	Bunch charge	Bunches per train	**Electrons per train**
Drive Beam	**2.4 → 0.24**	50 Hz	**244 ns**	12 GHz	8.4 nC	2922	**1.53e14**
Main Beam	**9 → 1500**	50 Hz	**156 ns**	12 GHz	0.6 nC	312	**1.16e12**

2 Main Beam (MB) linacs (21 km each)
2 * 24 Drive Beam (DB) decelerators (≈ 875 m each)

Baseline BLM for CLIC Two-Beam-Module

- Primary role of the BLM system as part of the Machine Protection System is to **prevent subsequent injection** when potentially dangerous beam losses are detected ("next cycle permit")
- Option of CLIC at 100 Hz → minimum response time <8 ms required by BLMs to allow post pulse analysis
- Ionization chambers fulfill necessary requirements for machine protection and diagnostics
  - LHC ionization chamber and readout electronics
    - Dynamic range 10^5 (10^6 under investigation)
    - Sensitivity $7e10^{-9}$ Gy
- See: *CLIC collaboration, "A multi-TeV linear collider based on CLIC technology - CLIC Conceptual Design Report, Volume 1. Technical report", CERN, Geneva, 2012*

Sensitivity and Dynamic Range

- Considerations for the CLIC BLM system:
  - Damage to beam-line components, determined by power density (not by beam power) of the beams
    - → Upper limit of dynamic range: 10% of destructive loss
    - Simulated as localised loss
  - Luminosity losses due to beam loading variations due to beam losses
    - → Lower limit of dynamic range: 1% (CDR) or 10% (fibers) of acceptable operational losses
    - Simulated as distributed loss
- Other considerations:
  - Damage to electronics (single event effects, lattice displacement, total ionising dose)
  - Activation (access issues)
  - Failure scenarios under investigation (PLACET simulations for the two-beam-module ongoing)

Alternative Technology

- Baseline: High costs due to the large number of BLMs required
  - >45 thousand quadrupole magnets over 42 km (41.5 thousand in the Drive Beam)
    → Investigate alternative technologies for the two-beam-modules in the post CDR phase
  - Technologies that cover a large distance along the beam-line
    - E.g. long ionisation chambers, optical fibers
- Topics under consideration:
  - Dynamic range and sensitivity
  - Signal dependence on incident angel of charged particle and on beam energy
  - Resolution of longitudinal position and time
  - Distinguish between losses of main beam and drive beam
  - Radiation hardness, exchange intervals
  - Photon sensors and read-out (dynamic range, radiation tolerance)
  - Calibration

Cherenkov Fiber BLMs

BLM based on Cherenkov Effect in Multi-mode Fibers

- Advantages
  - Cherenkov effect is an instantaneous process
  - Only sensitive to charged particles → insensitive to gamma radiation (and therefore background from activation)
  - Very small, diameter <1 mm
  - Cherenkov quartz is radiation hard (compared to scintillating fibers)
  - Insensitive to magnetic field and temperature fluctuations

- Possible disadvantages
  - Lower sensitivity compared to scintillating fibers (which give about 1000 times more light output)
    - A low proportion of the produced Cherenkov light reaches fiber end face
  - Angular dependent response
  - Radiation effects: e.g. radiation induced attenuation

Cherenkov Fibres – Detection Principle

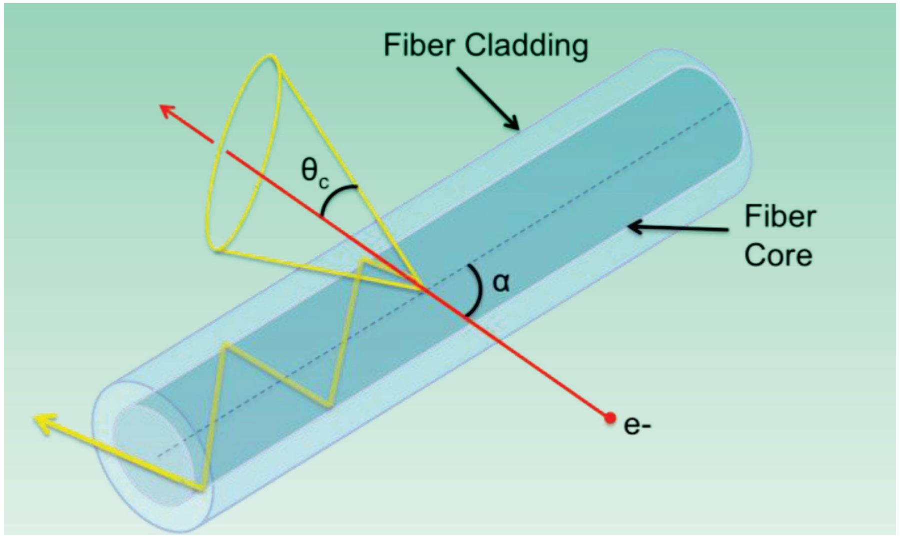
- When a charged particle with v>c enters the fiber, photons are produced along Cherenkov cone

$$\cos\theta_{Cherenkov} = \frac{1}{n_{core}\beta}$$

- Light yield depends on:
  - Fiber diameter
  - Numerical Aperture (NA)

    $$\mathrm{NA} = \sqrt{n_{core}^2 - n_{clad}^2}$$

    n … index of refraction
  - α … angle between particle track and fiber axis
  - β … particle velocity

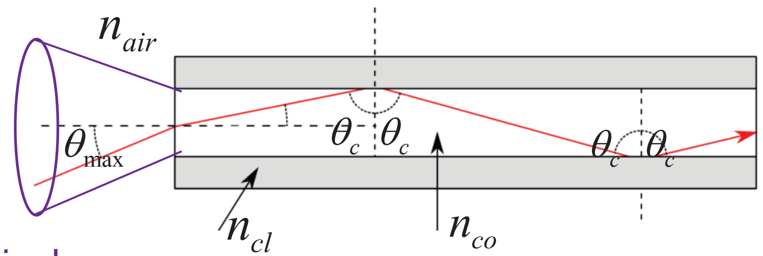


Cherenkov Light Signal in Fibers (J. van Hoorne, Master Thesis)

- **Analytical model** calculates (as function of incident particle velocity and angle) probabilities:
  - P_t propagating produced photons inside the fiber
  - P_e photons exiting at the fiber end face
  - $P_{e,a}$ photons exiting within nominal acceptance cone

$$P_{e,a} \propto \cos^{-1}\left[\frac{\beta\sqrt{n_{core}{}^2 - \mathrm{NA}^2} - \cos\alpha}{\sin\alpha\sqrt{\beta^2 n_{core}{}^2 - 1}}\right]$$

Analytical expression from:
S.H. Law et al., Appl. Opt. 45(36):9151-9159, 2006



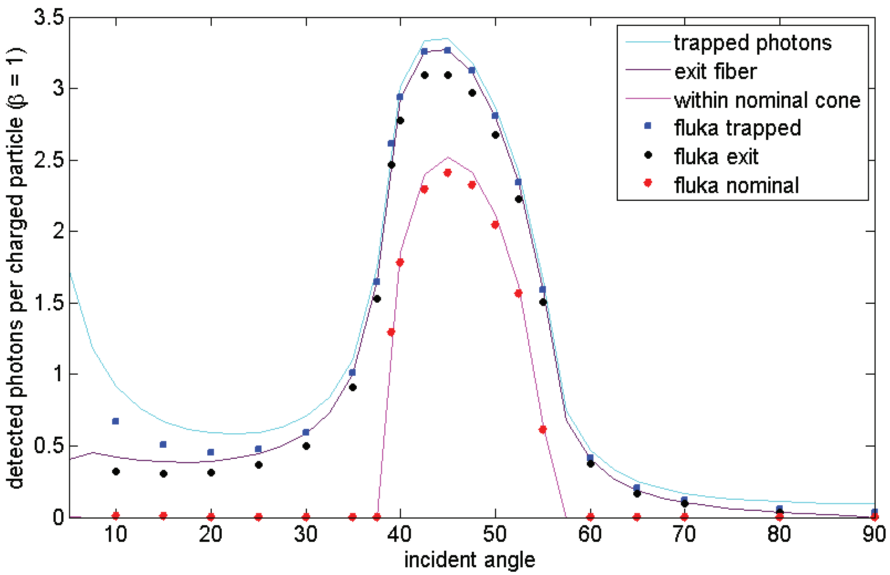
nominal acceptance cone

$$n_{air}\sin\theta_{max} = \mathrm{NA} = \sqrt{n^2{}_{core} - n_{clad}{}^2}$$

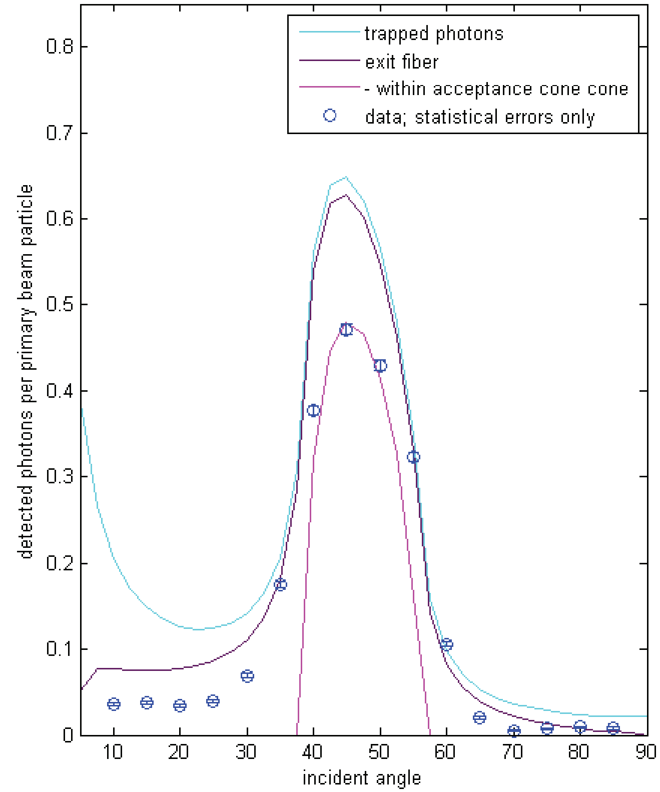
θ_c Critical angle (total reflection)

Cherenkov Light Signal in Fibers (J. van Hoorne, Master Thesis)

- **Test beam measurements with 120 GeV protons** to compare with model:
  - Angular dependency
  - Diameter dependency
  - Time dispersion
- **Comparison analytical model and FLUKA**



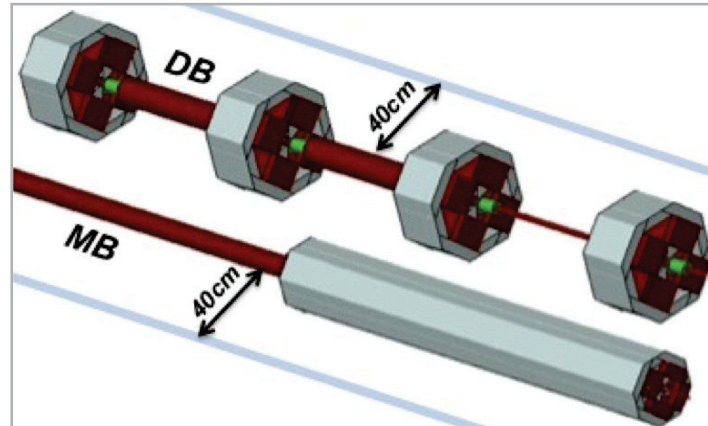
J. van Hoorne



Results angular dependency of the photon yield in a fiber (d_{fiber}=0.365 mm, NA=0.22, L_{fiber}≈4 m)

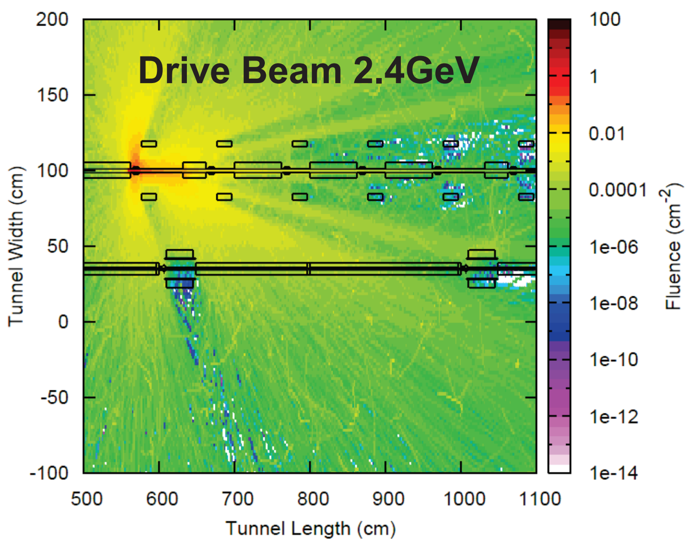
FLUKA Simulations of Loss Scenarios (S. Mallows)

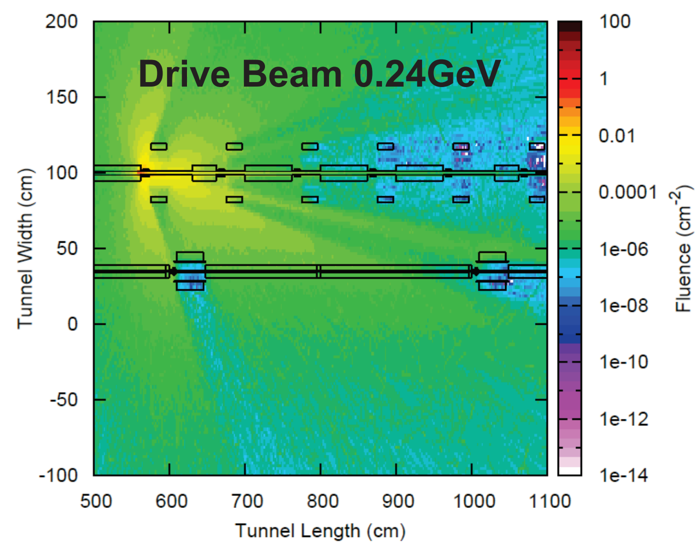
- FLUKA model to simulate secondary particle shower distribution at possible fibre locations
- Score **angular and velocity distribution** of charged particles
- → use as input to the analytical model to determine the photon signal at the end of the fibers



Blue lines indicate location of boundaries for scoring particle shower distribution (5 cm high)

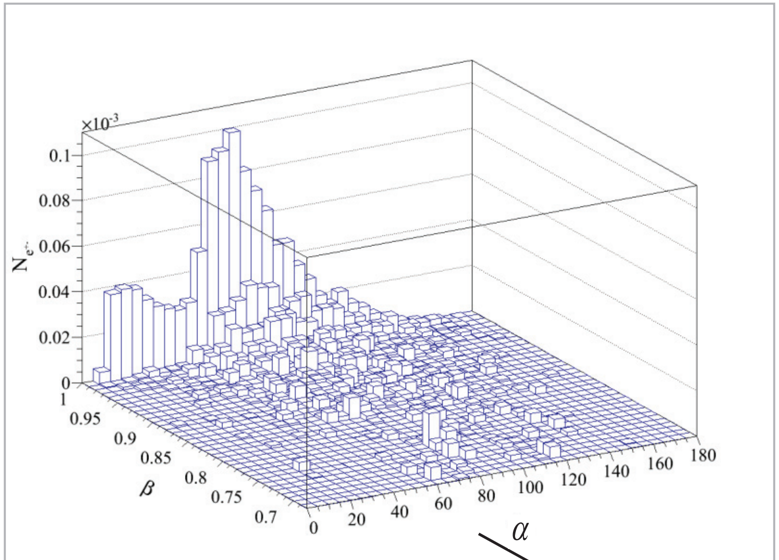
e+/e- fluence per primary electron impacting at single aperture



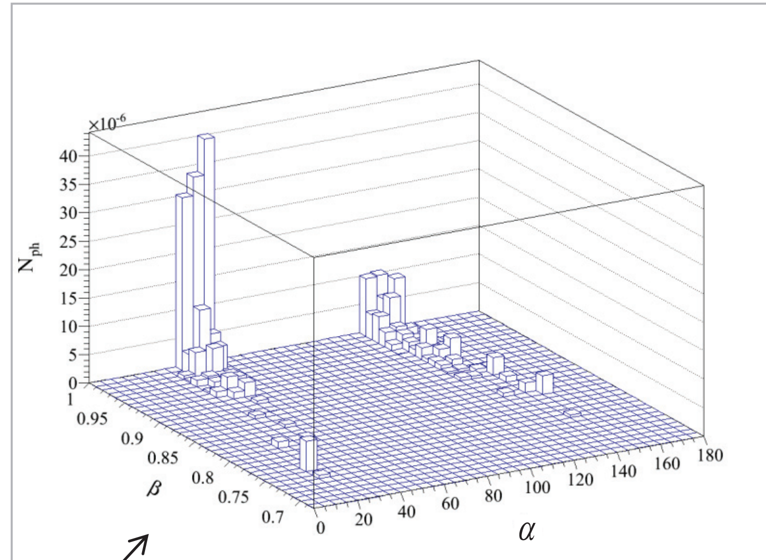


Photons Propagated in Fibers, Single Loss, 2.4 GeV DB

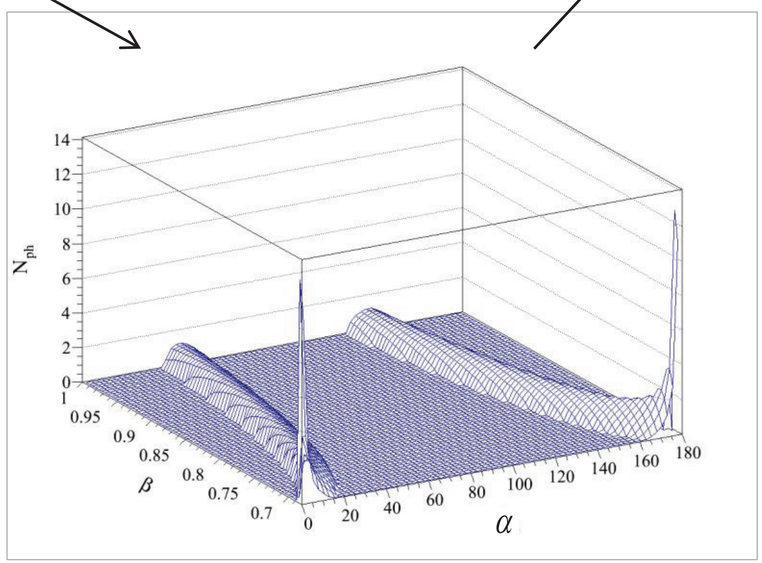
Particle Shower Distribution (FLUKA)



Corresponding Propagated Photons



Loss shower distribution, normalised to one lost beam electron



Propagated photon distribution, normalised to one lost beam electron

Photon yield N_{ph} for single charged particle as function of impact angle α and β=v/c

Fiber diameter 0.365 mm, NA 0.22

Sensitivity and Dynamic Range – CLIC Drive Beam

- Fiber: d=365 µm; NA = 0.22; 100 m long

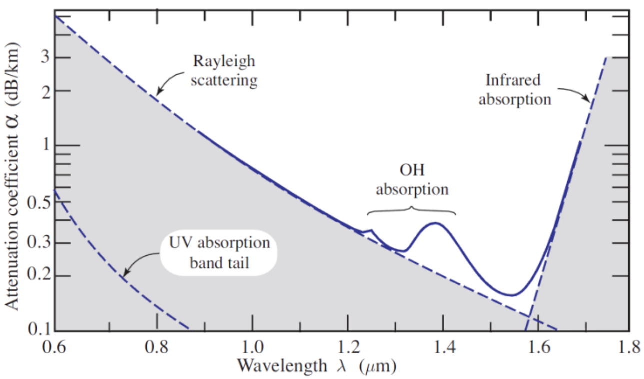
- **≈ 50% more photons downstream**
- Sensitivity requirements: need to measure ≈ $10^4 - 10^5$ N_{ph}/train
- Dynamic range: ≈ 10^4
  - With an identical detection system all along the Drive Beam (factor 10 from the different beam energies: 2.4 – 0.24 GeV)

- 244 ns long bunch train in the drive beam
- Single loss location: 244 ns arrival duration of photons at detector
- Longitudinally distributed losses:
- Arrival duration of photons at the detector
  - ≈ 410 ns downstream
  - ≈ 910 ns upstream

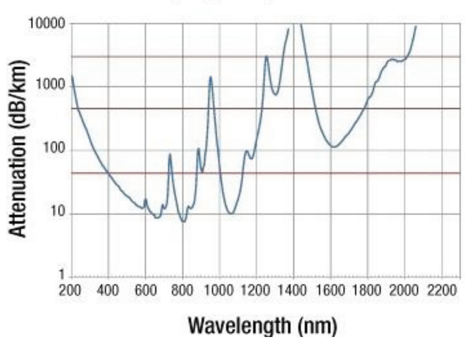
Attenuation

- In the UV/VIS range (λ=300 to 700 nm) the dominant attenuation effect in optical fibers is Rayleigh scattering; attenuation coefficient is proportional to λ^{-4}
- Therefore, for fibers longer than 200 m the blue/green part of the radiation spectrum becomes insignificant

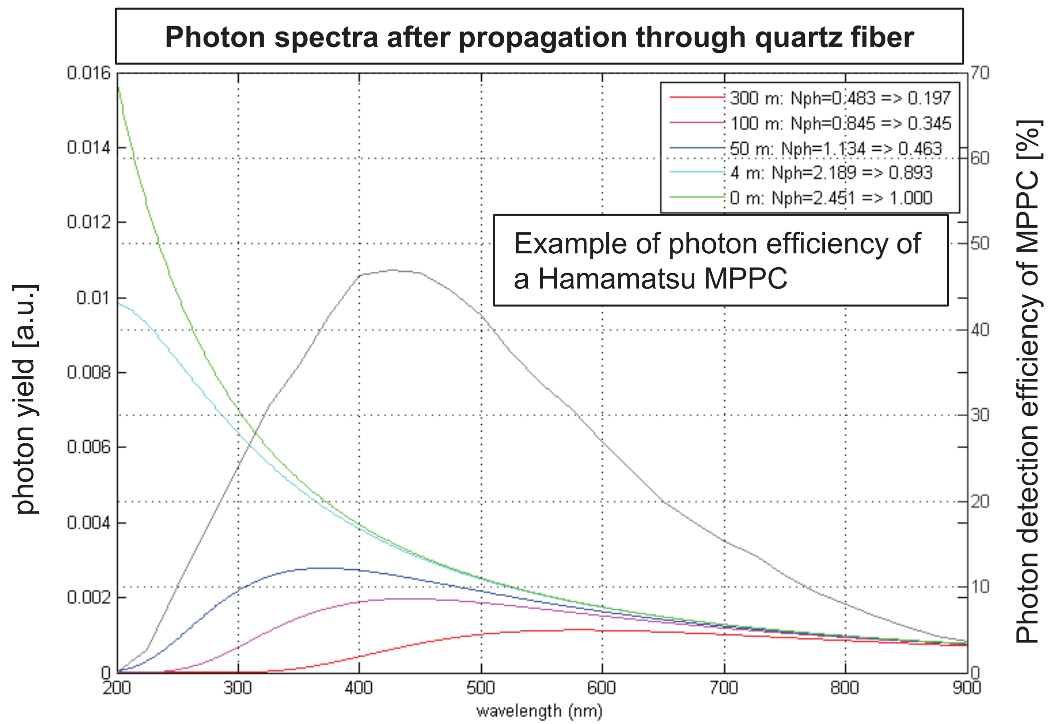
→ fibers should not be longer than ≈ 100 m



0.22 NA, High-OH, Multimode Fiber

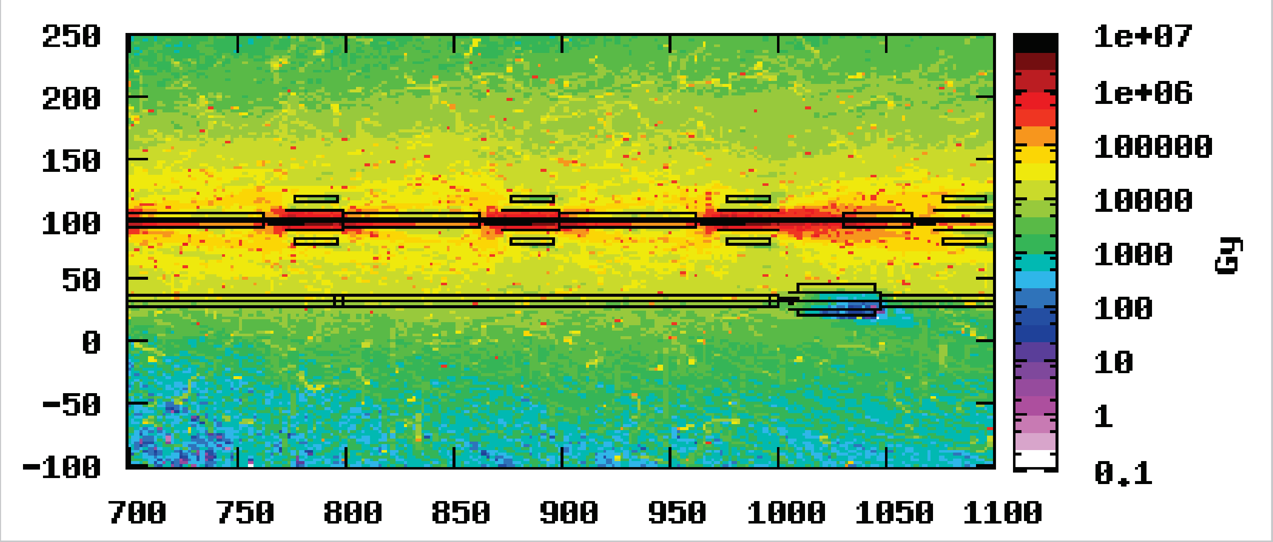


Additional absorption bands from impurities



Radiation Hardness

- Annual dose ≤ 50 kGy at fiber location
- CMS quartz calorimeter fibers: some tested ok up to 22 MGy *(P. Gorodetzky et al., NIMA 361:161-179, 1995; and V. Hagopian, CMS-CR-1999-002)*
  - Beware of wavelength dependence!
- Radiation Induced Absorption strongly depends on fiber materials and manufacturing conditions → Careful selection and radiation testing is necessary *(J. Kuhnhenn, DITANET Workshop on Beam Loss Monitoring, 2011)*
  - In general: High OH content, pure silica core step-index fibers with F-doped cladding
  - Future: solarisation resistant fibers (being developed for UV applications) might be an option

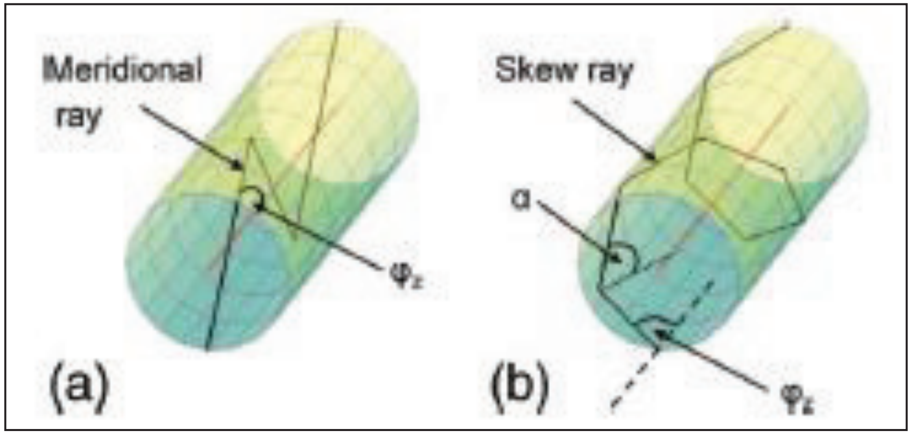


Annual absorbed dose from maximum permissible losses in Drive Beam at 2.4 GeV (main contribution), assuming 180 days running at nominal intensity

Longitudinal Resolution

Longitudinal Resolution

- BLM - Primary role as part of Machine Protection System
  → Detecting the integrated loss signal sufficient
- However, for beam diagnostics: desired longitudinal resolution is the distance between quadrupole magnets → 1 m in the Drive Beam
- Long bunch trains:
  - Drive Beam: 244 ns or ≈ 80 m
  - Main Beam 156 ns or ≈ 50 m
- Dispersion effects: Arrival time depends on photon trajectory in fiber
  → block skew rays by collimation

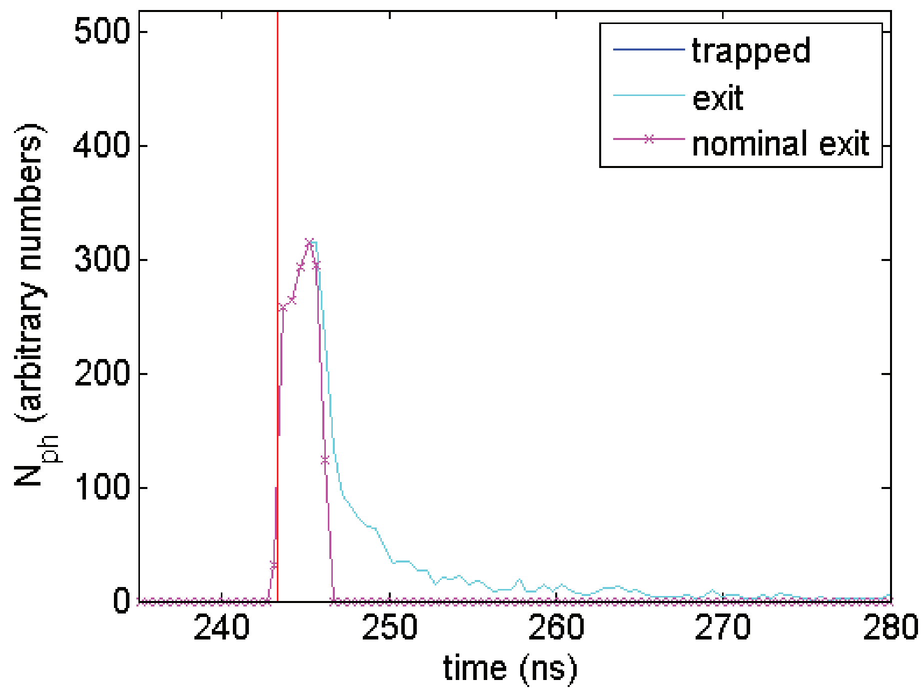


S. H. Law et al.

Single Bunch Resolution

- Arrival time distribution simulated for Drive Beam loss scenarios and 100 m fiber
  → **For single pulse (e.g. test beam)** and ns time resolution of the photon detection, a **position resolution of ≈< 1 m** is achievable
- **Rising edge** of the photon signal < 1 ns
  - Downstream: 0.7 m
  - Upstream: 0.12 m

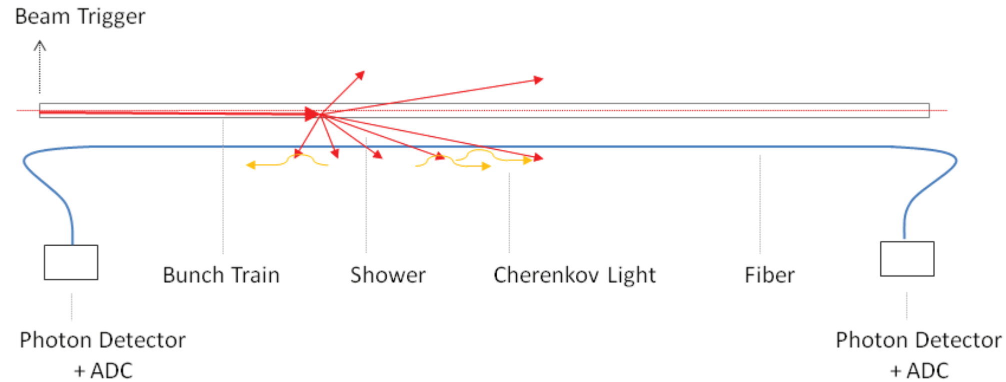
Example:
Simulation of photon arrival time distribution at an 'upstream' photon detector considering particle shower from a destructive Drive Beam loss;
fiber 365um core diameter, NA = 0.22



Multi Bunch Trains

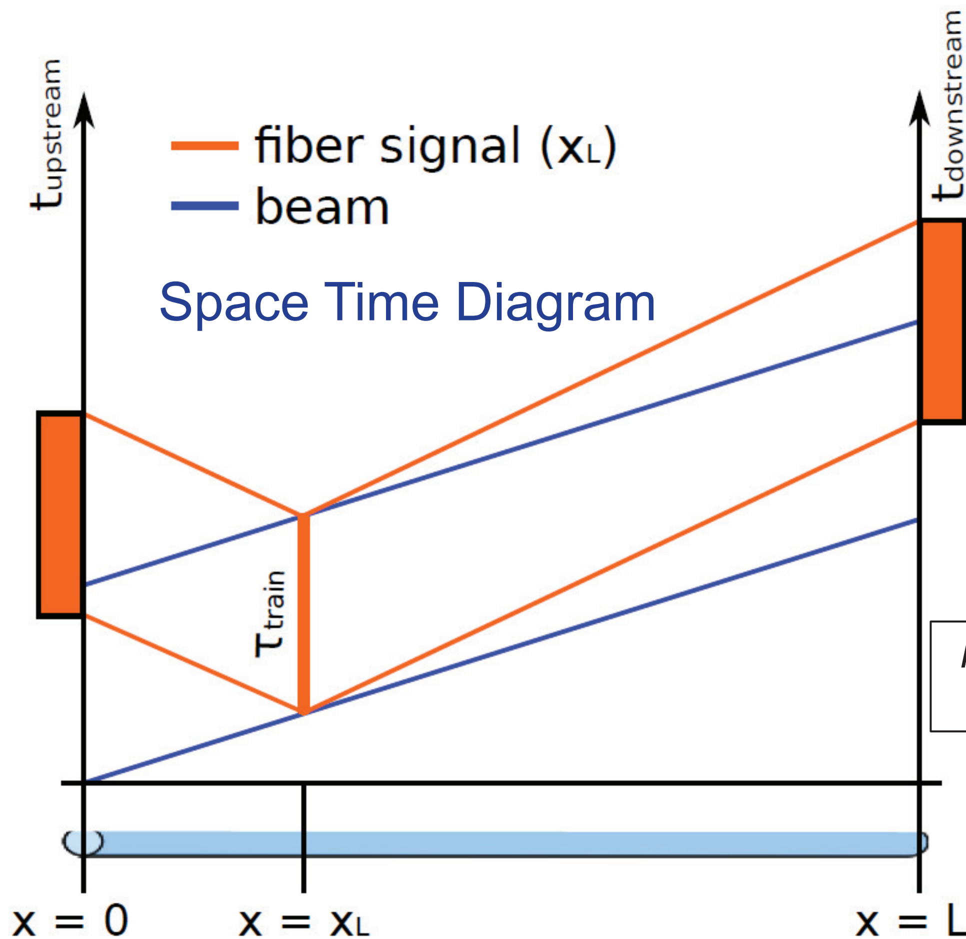
- In general it is not possible to reconstruct an arbitrary loss pattern (in position and time)
- But, only a couple of different loss patterns are to be expected:
  1. Single or multiple individual loss locations
     - Constant losses in time, i.e. obstructions
     - Variation in time, i.e. interaction with "dust"
  2. Losses building up along the train, starting at a certain position and/or bunch number (i.e. long range or resistive wall wake fields)
     - Combined with aperture limitation
  3. Constant losses (i.e. beam gas)
  4. Equipment failures
  5. Others?
- Can these scenarios be distinguished? What is the resolution?
- Do all scenarios need the same longitudinal resolution?
- Additional measurements to improve?
  - E.g. fast, localised detector every ≈ 20 – 100 m to measure loss structure within the train (e.g. diamond BLM)

Single Loss Location – Constant for All Bunches



Starting point of the losses can be determined from the **signal rising edges**, with:

- < 1m longitudinal resolution
- ≈ 1ns time resolution

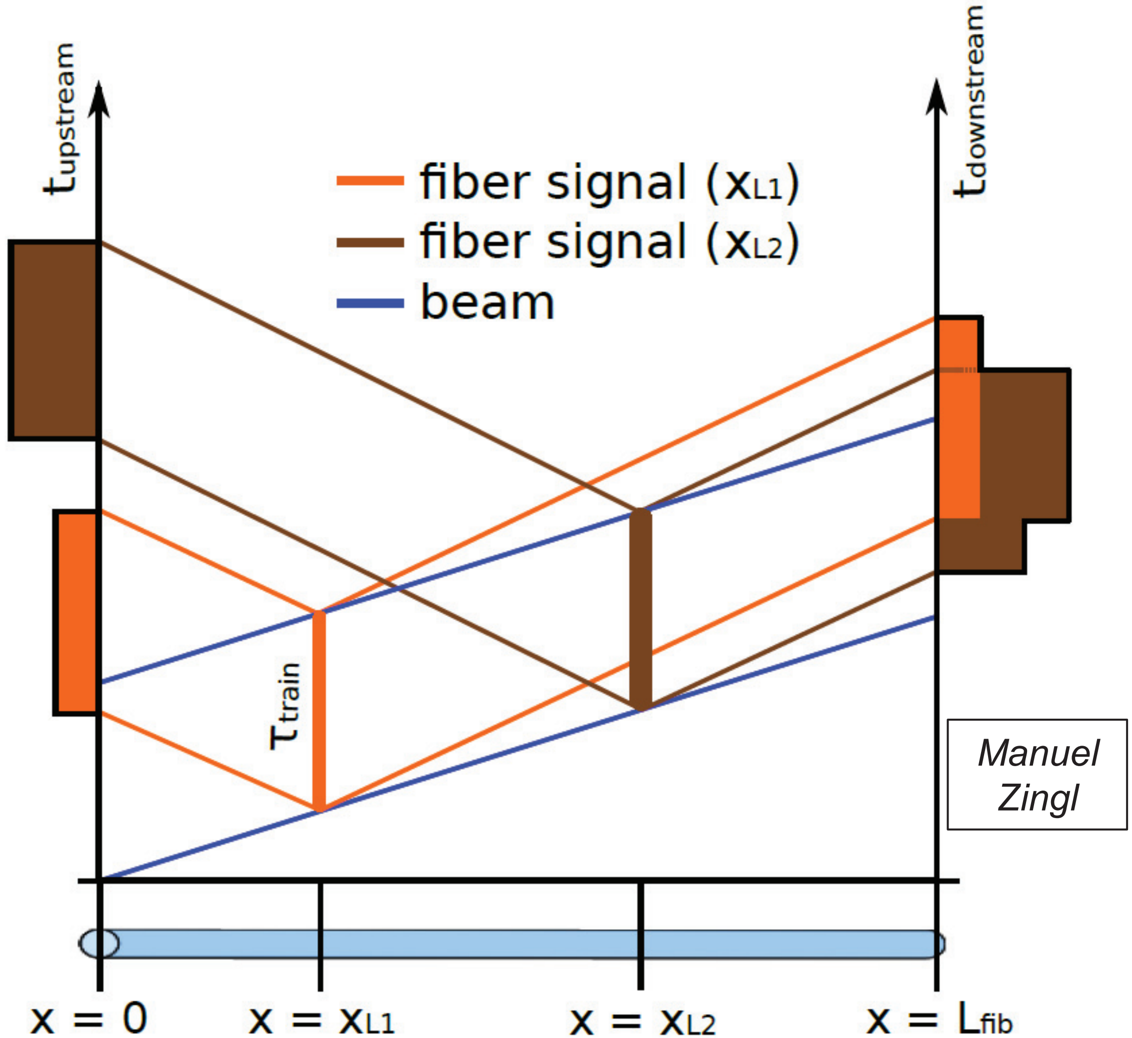


Manuel Zingl

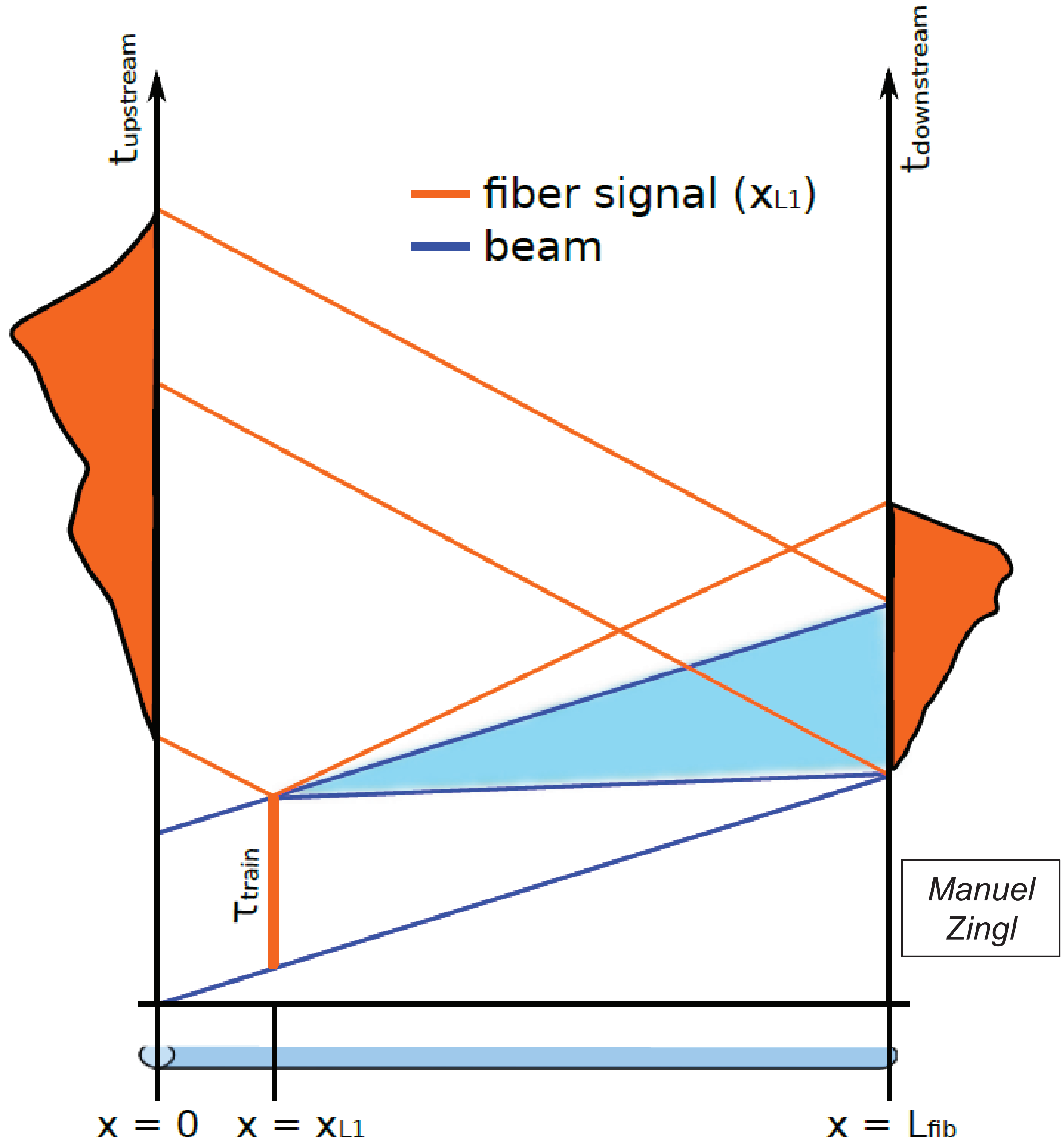
Two Loss Locations – Constant for All Bunches

Starting point of the losses can be determined from the **signal rising edges**, with:

- < 1m longitudinal resolution
- ≈ 1ns time resolution



Losses Building up Along the Train



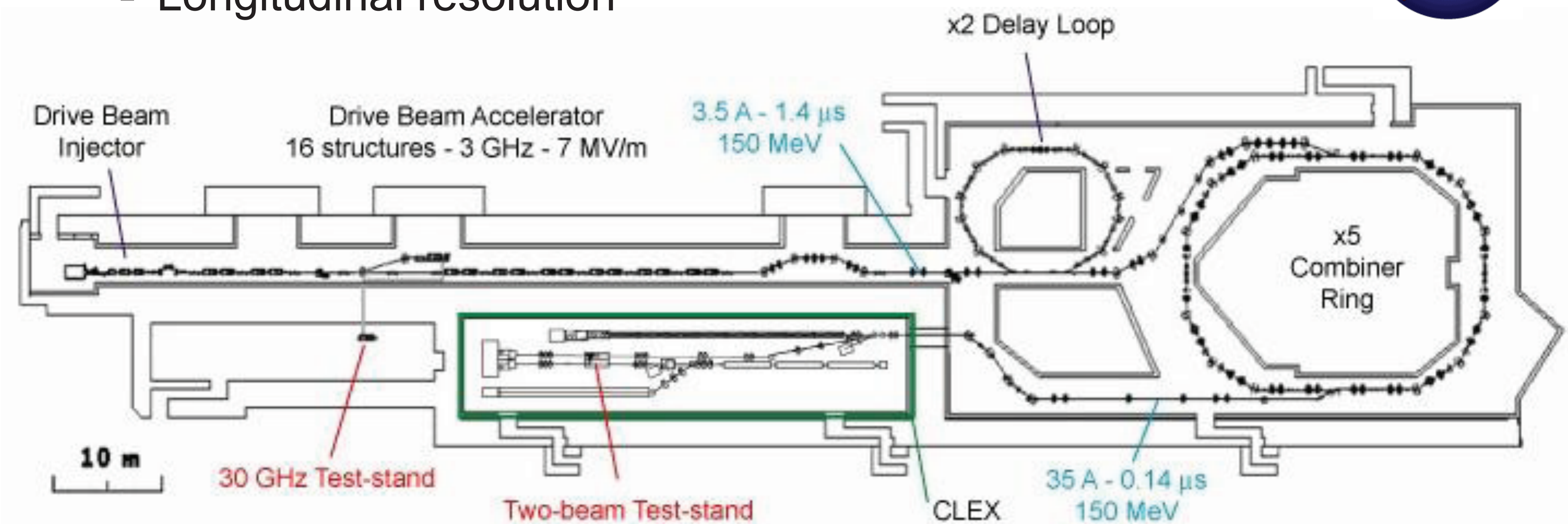
Summary and Outlook

Summary

- Dynamic range and sensitivity
  - Drive Beam:
    - 100 m fiber with 365 μm diameter and Silicon photomultipliers (SiPM) seems appropriate
  - Main Beam:
    - Tuning of simulations (loss scenarios) needed and higher statistics
    - 10 times less quadrupoles → can be covered by individual monitors (e.g. ionisation chambers, diamonds)
- Dependence on incident angel of charged particle and on beam energy
  - FLUKA simulations and modeling show that OK for drive beam
- Resolution of longitudinal position and time → under investigation
- Radiation hardness, exchange intervals? → chosen fibers to be tested

Further Outlook

- Investigate other possible loss scenarios
- Other signal sources (dark current, RF breakdown, backscatter from Drive Beam dumps)
- Integration of BLMs in Two-Beam-Modules (fibers along tunnel wall?)
- CLIC Test Facility (CTF3): Fiber BLM and 8 ACEMs (‘localised’ BLMs) installed
  - Operational losses
  - Longitudinal resolution



Thank You for Your Attention

SPARE SLIDES

Sensitivity and Dynamic Range – CLIC Drive Beam

- Number of photons exiting within the acceptance cone; loss at a single aperture; d=365μm; NA = 0.22

Destructive Loss		
	N_{ph}/train travelling Downstream	N_{ph}/train travelling Upstream
DB 0.24 GeV	$4.3\cdot10^{7}$	$2.8\cdot10^{7}$
DB 2.4 GeV	$5.4\cdot10^{8}$	$3.7\cdot10^{8}$

- Sensitivity: 10% of acceptable operational loss
- Dynamic Range for downstream detection: Considered Arrival duration of the photons 410 ns, 100m fiber, 0.365 mm, NA 0.22

	Sensitivity (N_{ph}/train)	Dynamic Range
DB 0.24 GeV	$2\cdot10^{4}$	$4\cdot10^{2}$
DB 2.4 GeV	$4\cdot10^{4}$	$3\cdot10^{2}$

Considerations in TBMs:

- Possible failure scenarios in two beam modules under investigation (PLACET Simulations, CERN: TE-MPE-PE)
- → For BLM, detection requirements: Consider destructive limits (fraction of beam hitting single aperture). Destructive potential: **not** determined by Beam Power but by Power Density, i.e. Beam Charge/ Beam Size.
  - Main Beam (damping ring exit) 10000 * safe beam

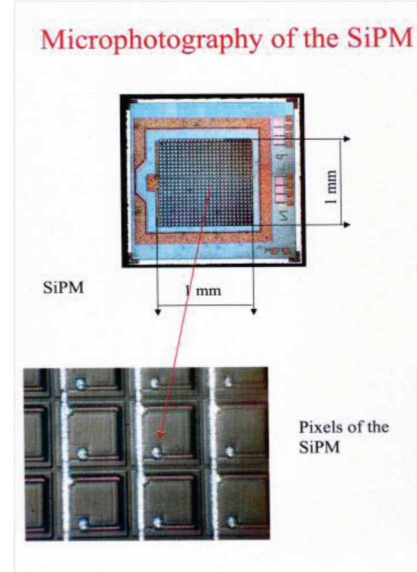
    0.01% of a bunch train – 1.16e8 electrons
  - Drive Beam decelerators 100 * safe beam

    1.0 % of a bunch train – 1.53e12 electrons

Cherenkov Fibers – SiPM as a Photodetector

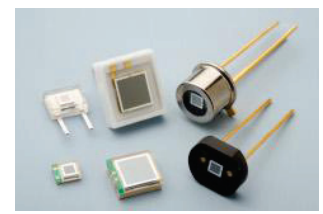
What is an SiPM?

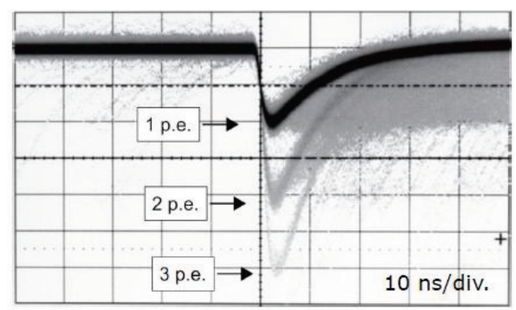
- Silicon Photomultiplier - array of APDs connected in parallel
- Each pixel is a p-n junction in self-quenching Geiger mode
- Reverse Bias causes APD breakdown
- Electron avalanche: PMT-like gain
- Pixels are equally sized and independent
- Analog output – Signal is sum of fired pixel signals



SiPM Advantages:

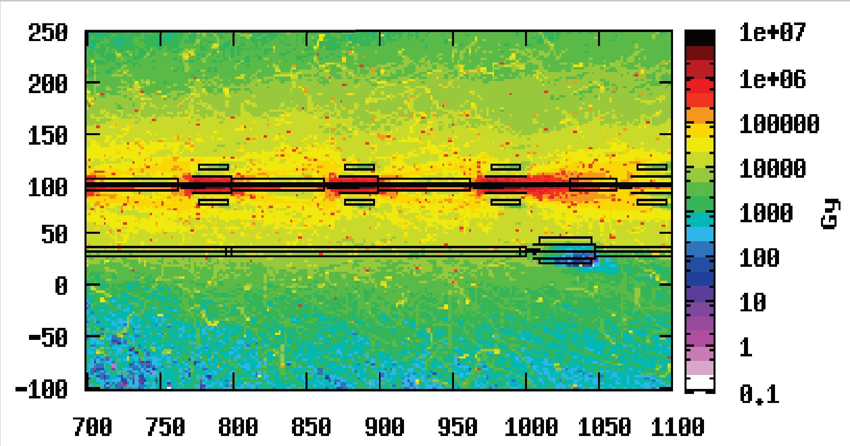
- Compact and light
- Low operating voltage (20-100V)
- Simple FE electronics
- Fast signal (~1ns)
- Cheap





Need to verify suitability:
Dynamic range, radiation hardness

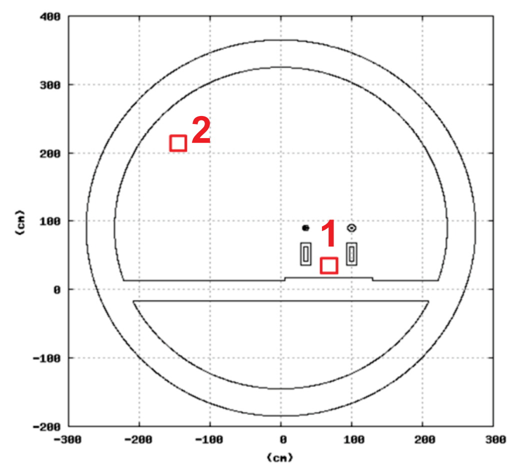
Radiation Levels



Annual Absorbed Dose from maximum permissible losses in Drive Beam at 2.4 GeV (assuming 180 days running at nominal intensity)

	Absorbed Dose Close to accelerator 1 (Gy year^{-1})	Absorbed Dose Close to tunnel wall 2 (Gy year^{-1})
DB – 240 MeV	≤10e4	≤10e3
DB - 2.4 GeV	≤ 10e5	≤10e4
MB – 9 GeV	≤10e4	≤10e3
MB – 1500 GeV	≤10e5	≤10e4

	1-MeV neutron eq. fluence Close to accelerator 1 (cm^{-2} year^{-1}),	1-MeV neutron eq. fluence Close to tunnel wall 2 (cm^{-2} year^{-1})
DB – 240 MeV	3.4e11	1.2e11
DB - 2.4 GeV	3.2e12	1.3e12
MB – 9 GeV	1.0e10	4.0e9
MB – 1500 GeV	8.5e11	3.1e11



Sensitivity and Dynamic Range – CLIC Drive Beam

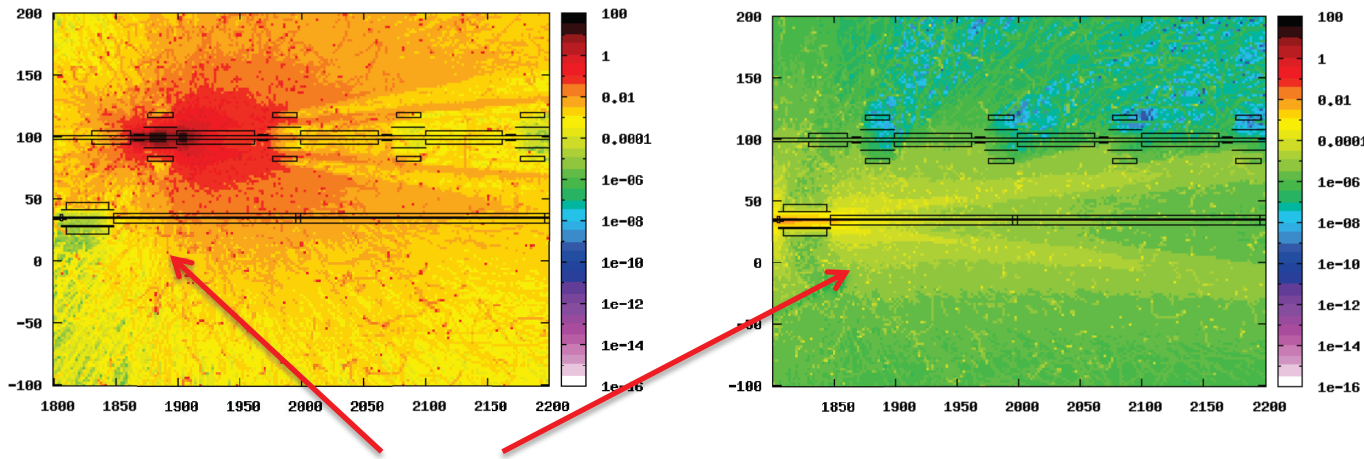
- Fiber: d=365μm; NA = 0.22; 100 m long
- 244 ns long bunch train in the drive beam
- Upper end of dynamic range:
  - Single loss location for destructive loss
  - 244 ns arrival duration of photons at detector
  - 10% of destructive loss
- Lower end of dynamic range:
  - Longitudinally distributed losses
  - arrival duration of photons at the detector (≈ 410 ns downstream and ≈ 910 ns upstream)
  - 10% of operational limit for detection sensitivity
- **≈ 50% more photons downstream**
- Sensitivity requirements: need to measure ≈ 10^4 – 10^5 N_{ph}/train
- Dynamic range: ≈ 10^4
  - With an identical detection system all along the Drive Beam (factor 10 from the different beam energies: 2.4 – 0.24 GeV)

Cross Talk

- Spatial distribution of prompt absorbed dose (Gy) from FLUKA simulations:

Destructive Drive Beam loss
1.0% of bunch train hits single aperture restriction

Destructive Main Beam loss
0.01% of bunch train hits single aperture restriction



- At the very beginning of the Main Beam: Destructive Drive Beam loss provokes similar signal as destructive Main Beam loss in the region close to Main Beam quadrupole
- **Not** a machine protection issue – **dangerous loss would never go unnoticed**
- Compare signals from both sides to distinguish Main and Drive Beam losses