Studies for the CLIC TBM Beam Loss Monitoring System

S.Mallows, E.B. Holzer, J. van Hoorne

BE/BI/BL

Outline

- CLIC BLM Considerations
  - Machine Protection Strategy
  - Beam Losses in the 2 beam modules
- Ionization Chambers as a Suitable Baseline Technology Choice
- Cherenkov Fibers as an Alternative Technology Choice
  - Development of “Model” to predict light yield
  - Use of model to predict signal for CLIC beam losses
- Ongoing Studies
  - Cross – Talk Issues
  - Longitudinal Position Resolution with Cherenkov Fibers
- Summary / Outlook

Machine Protection Strategy

- Based on **Passive protection** and a "**Next cycle permit**"
- Primary role of the BLM system as part of the Machine Protection System is to prevent **subsequent** injection into the Main Beam linac and the Drive Beam decelerators when potentially dangerous beam instabilities are detected.
- Option of CLIC at 100Hz → **Minimum Response time <8ms required by BLMs** to allow post pulse analysis

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

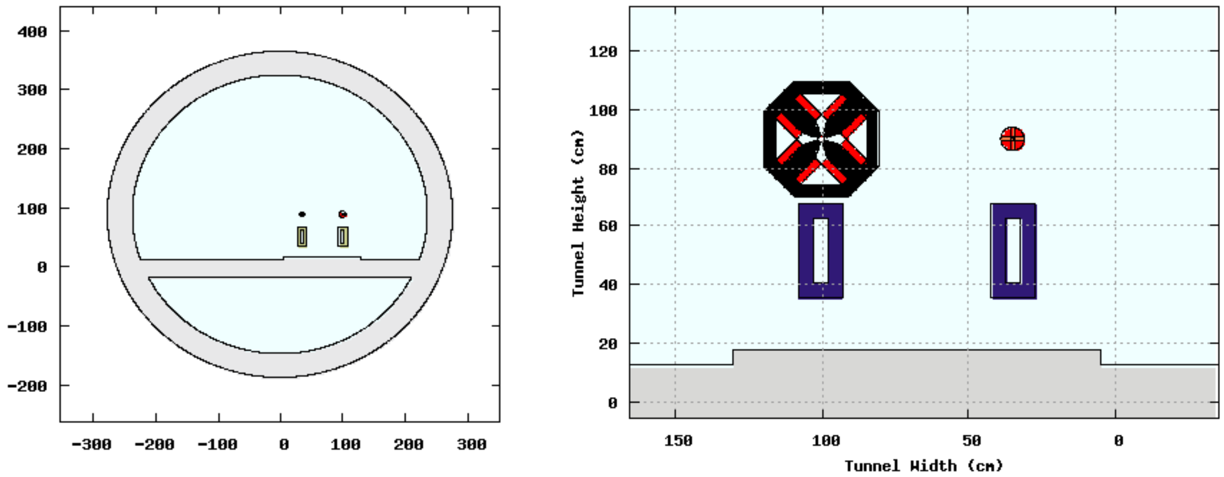
    1.0 % of a bunch train – 1.53e12 electrons

Limits in the Two Beam Modules

- **Beam Dynamics Considerations** *(luminosity losses due to beam loading variations)*
  - *10^{-3} of full intensity of the Main Beam over 21km linac*
  - *10^{-3} of full intensity of the Drive Beam over 875m decelerator*
- **Activation** *(Residual Dose Rates – Access Issues)*
- **Damage to beamline components**
- **Damage to electronics** (*SEE's, Lattice Displacement, Total Ionizing Dose*)

FLUKA Loss Simulations

- *Model includes tunnel, tunnel floor, beam line components and silicon carbide girders*

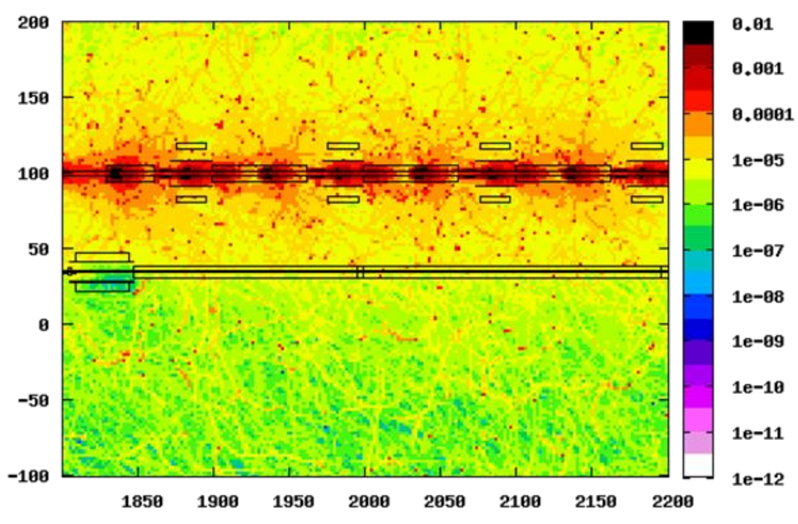


- *Loss location: End of PETS/Accelerating Structures just upstream of quadrupoles*
- *Drive Beam Losses at 2.4 GeV, 0.24 GeV*
- *Main Beam Losses at 1500 GeV, 9 GeV*

CLIC Conceptual Design Report, BI Chapter

Sensitivity Requirements

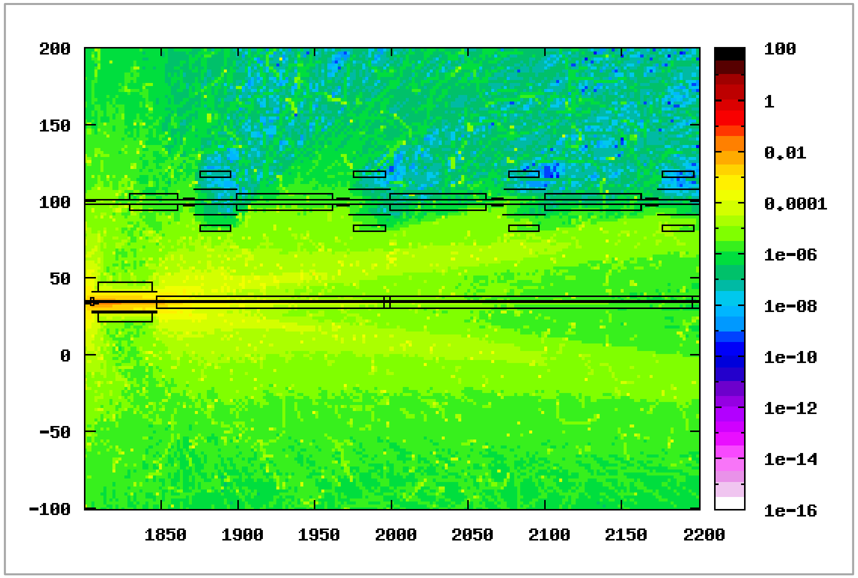
- *Standard Operational Losses (mainly due to beam gas scattering)*
- *FLUKA – losses are distributed longitudinally*
- ***Lower Limit of Dynamic Range**: 1% loss limit for beam dynamics requirements (to detect onset of such losses)*
  - *10^{-5} train distributed over MB linac, DB decelerator*



Example: Spatial distribution of absorbed dose for maximum operational losses distributed along aperture (DB 2.4 GeV) Scaling: 10^{-3} bunch train/875m

Destructive Losses

- *Detect onset of Dangerous losses*
- *FLUKA Loss at single aperture*
- ***Upper Limit of Dynamic Range,** 10% destructive loss (desirable)*
  - *0.1% DB bunch train, 0.001% bunch train MB*



Example: Spatial distribution of absorbed dose resulting from loss of 0.01% of 9 GeV Main Beam bunch train at a single aperture

CDR Summary Table for BLMS

Machine Sub-Systems	Dynamic Range	Sensitivity (Gy/pulse)	Response time (ms)	Quantity	Recommended
Main Beam					
e^- and e^+ injector complex	10^4	10^{-7}	<8	85	
Pre-Damping and Damping Rings	10^4	10^{-9} (Gy per millisecond)	1	1396	Insensitive to Synch. Rad.
RTML	10^4	10^{-7}	<8	1500	
Main Linac	10^6	10^{-9}	<8	4196	Distinguish losses from DB
Beam Delivery System (energy spoiler + collimator)	10^6	10^{-3}	<8	4	
Beam Delivery System (betatron spoilers + absorbers)	10^5	10^{-3}	<8	32	
Beam Delivery System (except collimators)	$>10^5$	$<10^{-5}$	<8	588	
Spent Beam Line	10^6	10^{-7}	<8	56	
Drive Beam					
Injector complex	$5.\ 10^4$	$5.\ 10^{-6}$	<8	4000	
Decelerator	$5.\ 10^6$	$5.\ 10^{-8}$	<8	41484	Distinguish losses from MB
Dump lines	tbd	tbd	<8	48	

CDR Summary for BLMS

- *Ionization Chambers fulfill necessary requirements for a machine protection system in TBMs*

- *LHC Ionization Chamber + readout electronics*
  - *Dynamic Range 10^5 (10^6 under investigation)*
  - *Sensitivity $7e10^{-9}$ Gy*

The MB linac and DB decelerator could also be safely operated at a reduced dynamic range, should 10^6 turn out to be too challenging

- *Large Number BLMs Required – Cost Concern*

→ *Investigate **Alternative Technologies** for the Two Beam Modules in the post CDR phase*
  - Technologies that cover a large distance along the beamline
  - E.g. long ionization chambers, optical fibers

BLMs based on Cherenkov effect in multimode fibers

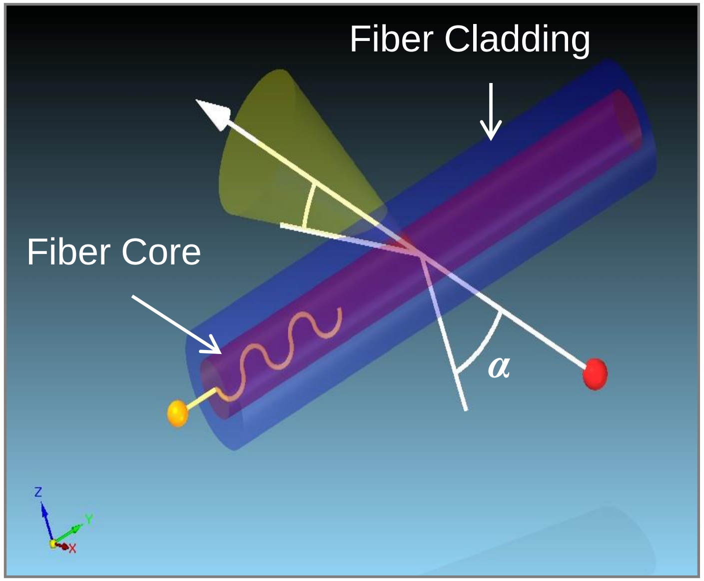
- Advantages
  - Fast process (time constant <1ns)
  - Only sensitive to charged particles → *Insensitive to gamma radiation (and therefore background from activation)*
  - *Very small, diameter <1mm*
  - *Cherenkov Quartz is radiation hard (c.f. scintillating fibers)*
  - *Insensitive to magnetic field, temperature fluctuations,*

- Possible Disadvantages
  - Lower Sensitivity c.f. 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: Radiation Induced Attenuation*

Cherenkov radiation

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

$$\cos\theta = \frac{1}{n_{co}\beta}$$



Need to Consider

- The **Number of photons generated** in fiber
- The **Proportion of those photons transmitted** (Cerenkov Efficiency)
  - **a function of β and α**

(for a given fiber diameter and Numerical Aperture, NA)

- *α - angle between particle track and fiber axis*
- *β - particle velocity*
- $NA = \sqrt{n^2_{core} - n_{clad}^2}$

Cherenkov Fibers – Analytical Model

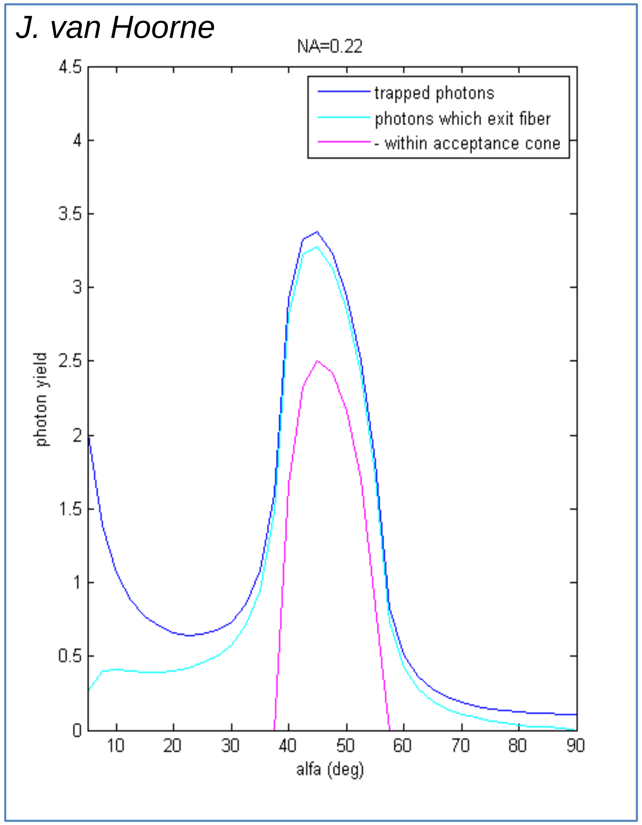
Development of Analytical Model for Cherenkov Light Signal in Fibers

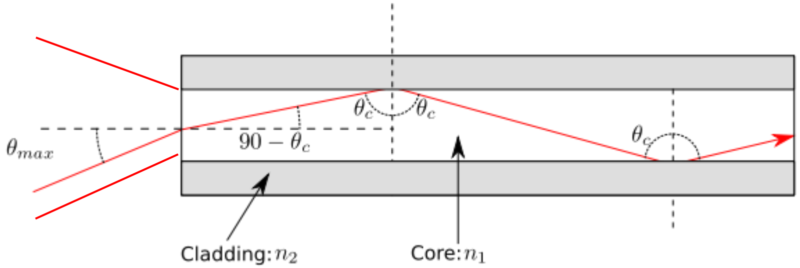
(by J van Hoorne , for Masters thesis)

- **Probability** of
  - **trapping** the produced photons inside the fiber P_t
  - trapped photons **exiting** at the fiber end face P_e
  - Photons exiting the fiber end face **within acceptance cone** $P_{e,a}$

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

- α *- angle between particle track and fiber axis*
- β *- particle velocity*
- $NA = \sqrt{n^{2}_{core} - n_{clad}^{2}}$
- $\theta_c = \sin^{-1}(n_{cl}/n_{core})$
- $\theta_{max} = \sin^{-1}(NA/n)$

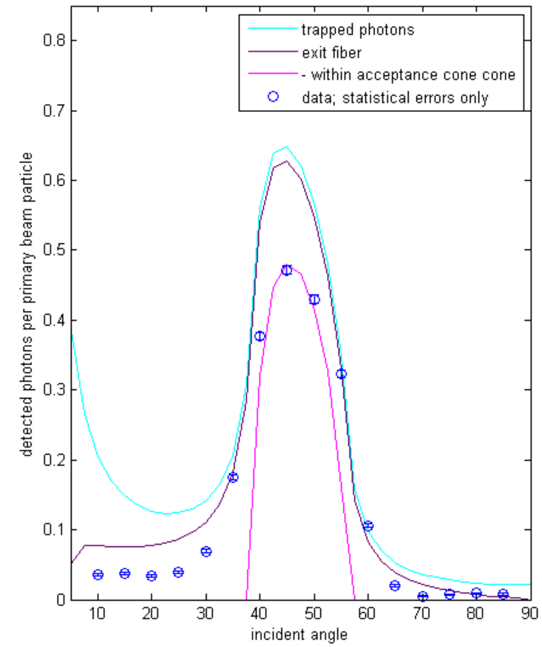




Cherenkov Fibers – Verification of Model

- *Verification of Analytical Model at test beam lines*
  - Test beams North Area, East Area
  - Fibers mounted on a rotable support, impacted by *120 GeV protons (North Area)*
  - *Angular Dependency*
  - *Diameter Dependency*

J. van Hoorne

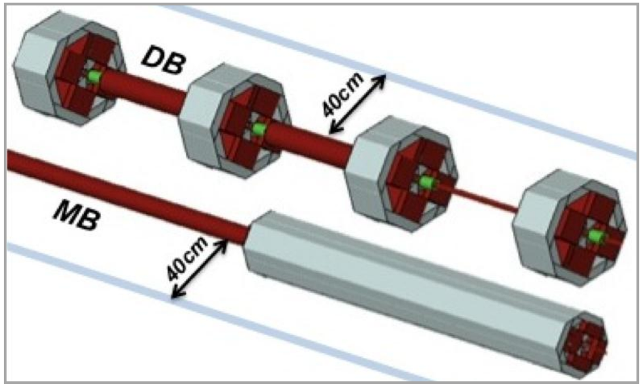


Results for the angular dependency of the photon yield in a fiber with:

- d_{fiber}=0.365mm
- NA=0.22
- L_{fiber}~4m

Cherenkov Fibers for CLIC TBMs (FLUKA)

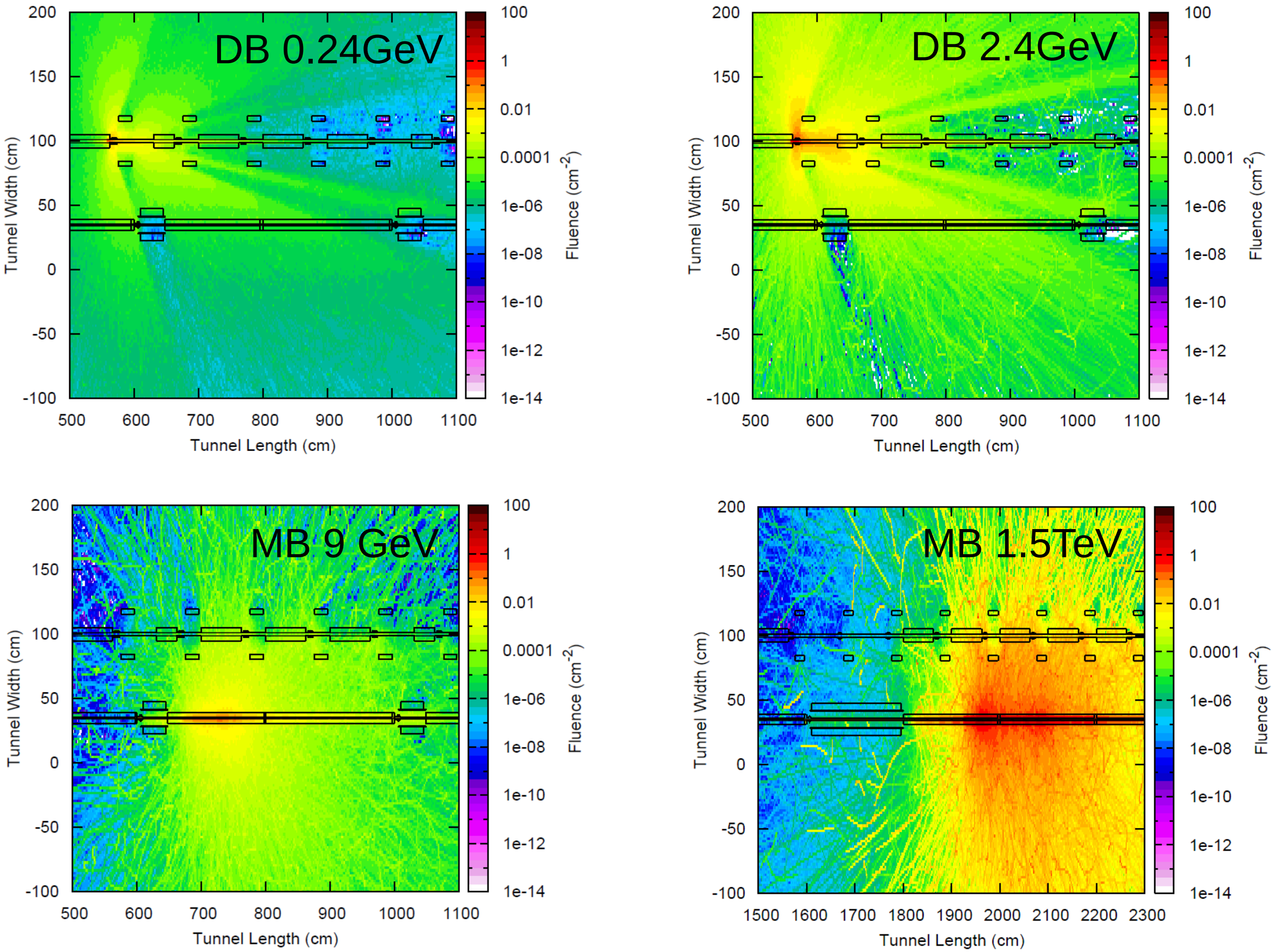
- Estimate of signal in fibers at CLIC TBMs
- *For Secondary Particle shower distribution, use FLUKA:*
  - Score **angular and velocity** distribution of charged particles at possible fiber locations
  - Boundaries 5cm high, 40cm from & parallel to beamline
- Determine number of photons use analytical model



Blue lines indicate location of boundaries for scoring particle shower distribution

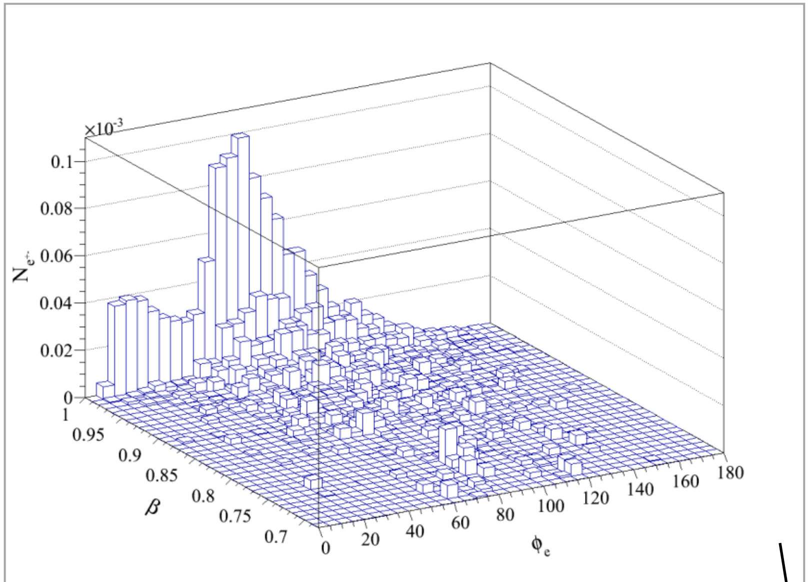
Cherenkov Fibers for CLIC, FLUKA Results 1

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



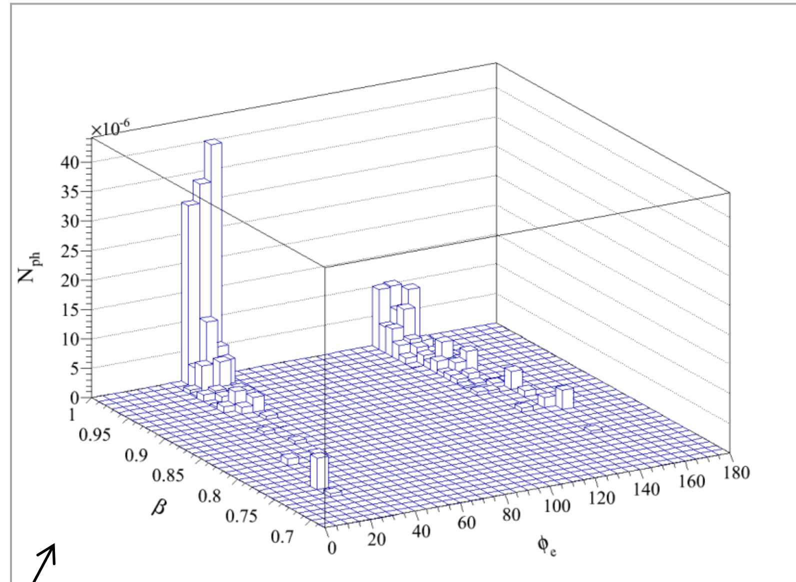
Photons in Cherenkov Fibers for CLIC, FLUKA Results 2

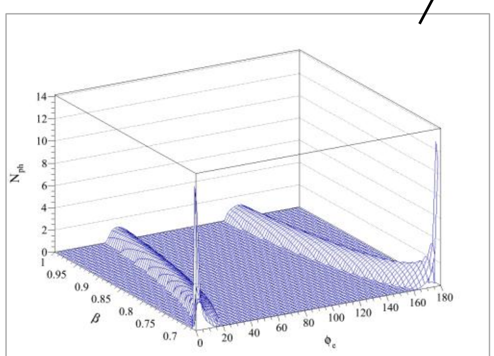
PARTICLE SHOWER DISTRIBUTION (FLUKA)



Loss shower distribution, normalized to one lost beam electron, for single loss at 2.4 GeV in the DB

CORRESPSONDING 'TRAPPED' PHOTONS





Trapped photon distribution, normalized to one lost beam electron, for single loss at 2.4 GeV in the DB. (Assuming Fiber Diameter 0.365mm NA 0.22)

Courtesy J van Hoorne

Photons in Cherenkov Fibers for CLIC Drive Beam

	Destructive Loss, (N_{ph}/train) (DS)	**Destructive Loss,** (N_{ph}/train) (US)
DB 0.24 GeV	$4.3 \cdot 10^{7}$	$2.8 \cdot 10^{7}$
DB 2.4 GeV	$5.4 \cdot 10^{8}$	$3.7 \cdot 10^{8}$

- *No. of trapped photons travelling in upstream (US) and downstream (DS) direction, loss at DB single aperture*

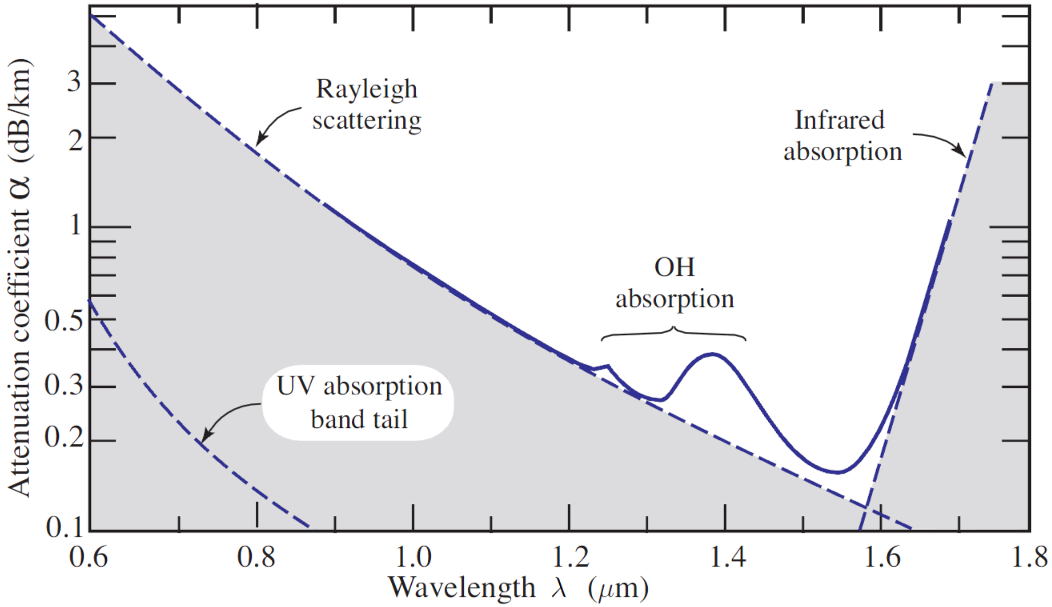
	Sensitivity* (N_{ph}/train)	**Dynamic Range**
DB 0.24 GeV	$5 \cdot 10^{1}$	10^{5}
DB 2.4 GeV	$5 \cdot 10^{2}$	10^{5}

- ***Sensitivity and dynamic range requirements*** *for a* ***downstream*** *photodetector allows the use of Silicon Photomultipliers (SiPM) (100m fiber)*
- *Dynamic Range (Considered Arrival duration of the photons 410 ns (DB) and 323 ns (MB) (100m fiber)0.365 mm fiber, NA 0.22*

Cherenkov Fibers – Attenuation

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

→ **Fibers should not be longer than ~100m**



Cherenkov Fibers – Longitudinal Resolution

- *BLM - Primary role as part of Machine Protection System*

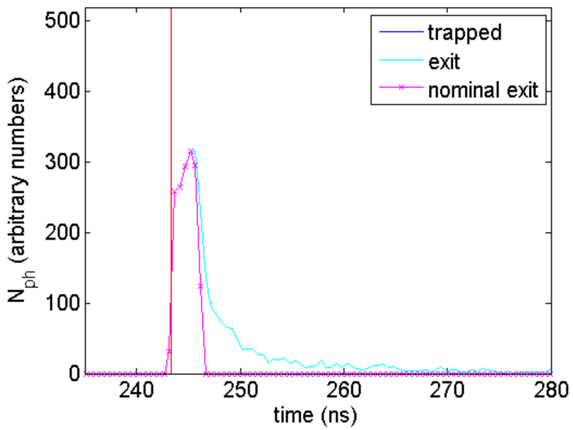
  → ***Detecting the integrated loss signal sufficient***

  - *However, **desired** longitudinal resolution is 1m, to detect **the location of the onset** of dangerous loss (or simply location where losses are higher)*

    Bunch trains in CLIC TBMs are long: 156ns, 244ns (~50m, 80m)

    What is the Achievable Resolution?

  - *First Consideration is Dispersion Effects*
    - *Arrival time distribution investigated for DB loss scenario.*
    - *Arrival time depends on various modes excited due to impact angle and due to impact point on fiber.*



Simplified model 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

Courtesy J van Hoorne

→ *For single pulse - With sufficient time resolution of the photo detection **the location** (~m) of **the onset of a destructive loss** could be determined (DB, 2.4 GeV)*

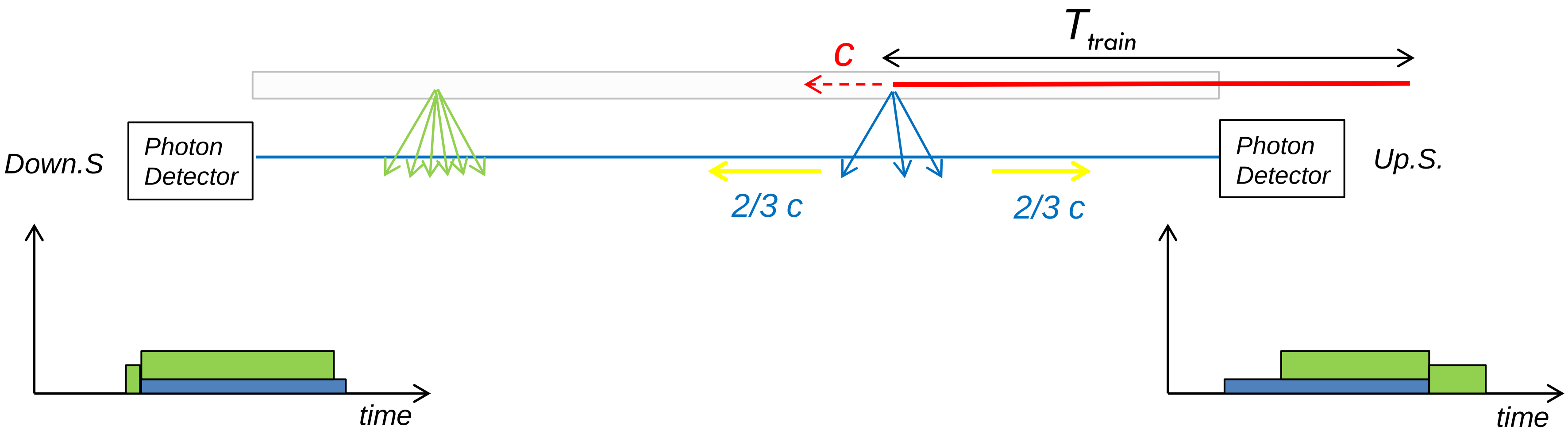
Cherenkov Fibers – Longitudinal Resolution

Not pilot beam: Multi-bunch trains

(not possible to resolve signal from individual bunches)

Simple Example - Assume uniform loss distribution along a train (which is unlikely)

Punctual Losses due to obstruction(s) in the beam line



*With sufficient photo-detection time resolution (~ns), **the location** (~m) of **the onset of a destructive loss** would still be seen in signal. DB, 2.4 GeV*

Longitudinal Resolution – Multi-bunch Effects

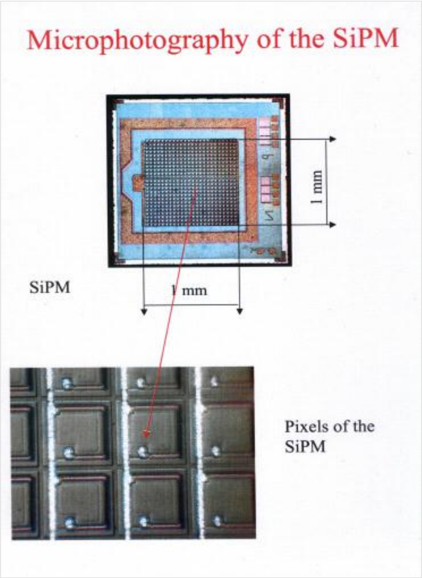
- *For NON-Uniform Loss Distribution along a train, which is likely e.g due to wakefield effects (MB)*
  - *Study in progress for Fibers*
    - *Multi Bunch Trains, Punctual Loss due to obstruction(s) in the beam line*
    - *It is possible to achieve similar position resolution for some complicated (non uniform) loss patterns along train.*

      Explained in detail in thesis (chapter 7) by J. van Hoorne.

- *For resolution loss structure within a train: Fibers **and** Ionization Chambers*
    - *Fast, sensitive and 'localized' detector every ~100m could be used to provide information on loss structure within train, and compared with signal from fiber or ionization chamber.*

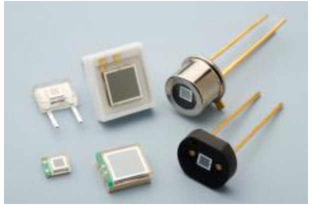
What is an SiPM?

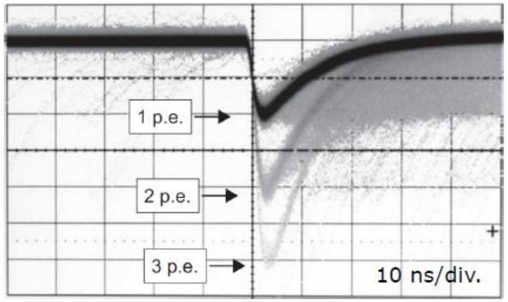
- Silicon Photomultiplier - array of APDs connected in parallel
- Each pixel is a p-n junction in self-quenching Geiger mode
- Reverse Bias causes APD breakdown
- Electron avalanche: PMT-like gain
- Pixels are equally sized and independent
- Analog output – Signal is sum of fired pixel signals



SiPM Advantages:

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

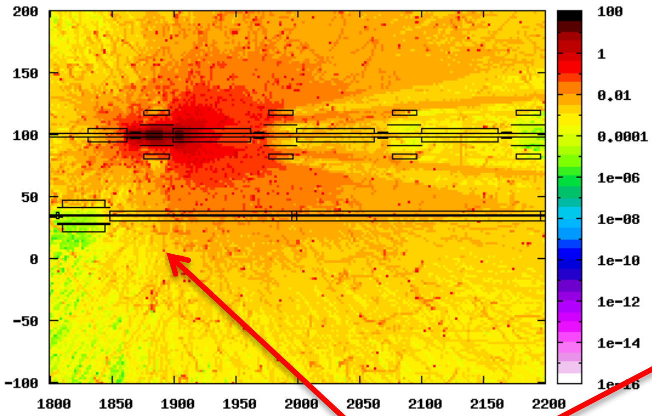




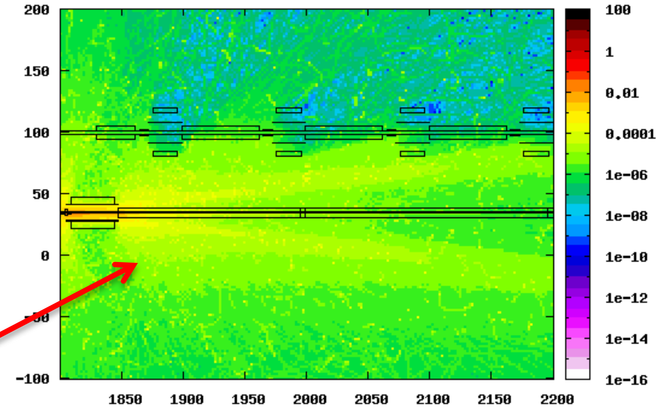
Need to verify suitability:
Dynamic range, radiation hardness

- Desirable to distinguish between a failure loss from each of the beams
- Spatial Distribution of prompt Absorbed Dose (Gy) from FLUKA Simulations:

Destructive DB 1.0% of bunch train hits single aperture restriction



Destructive MB 0.01% of bunch train hits single aperture restriction



- Loss of 1.0% in DB provokes similar signal as a loss of 0.01% of MB in region close to MB quadrupole.
- NOT a Machine Protection Issue – **Dangerous loss would never go unnoticed**
- **Compare signals from both fibers each side to distinguish Main and Drive Beam losses.**

Summary & Outlook

- *Cherenkov Fibers could be a reasonable alternative technology choice for the Drive Beam*
- *Further work required on Loss Scenarios/Simulations for TBMs*
  - *Simulations for MB require better statistics to predict signal in fibers*
  - *Sensitivity of particle shower distribution to FLUKA representation of the loss pattern (impact angle etc.), magnetic field, geomtery, etc*
  - *Investigate other possible loss scenarios*
- *Cross Talk between beams for Cherenkov Fibers*
- *Cross Talk considering other sources (RF breakdown, backscatter from DB dumps)*
- *Investigation radiation hardness of fibers*
- *Hardware Considerations*
  - *Depends on BLM technology choice*
  - *Balance cost with desired position resolution, etc*

Summary & Outlook

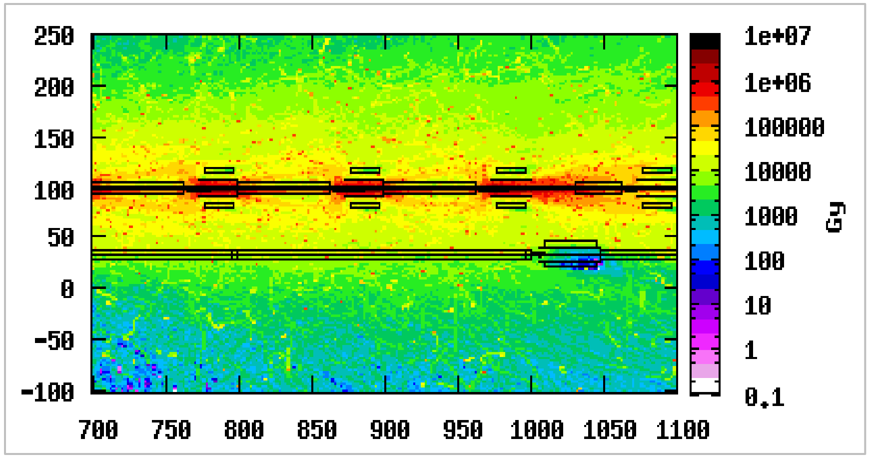
- *Integration of BLMs in Two Beam Modules*
  - *(fibers along tunnel wall etc?)*

- *Investigate Other Technologies*
  - *E.g. Single mode fiber bundles, long ionization chambers*

- *Testing at CTF 3*
  - *Fiber + 8 ACEMs ('localized' BLMs) at CTF3 Test Beam Line already installed*
  - *Compare signal fibers + ACEMs,*
  - *Achievable longitudinal resolution*

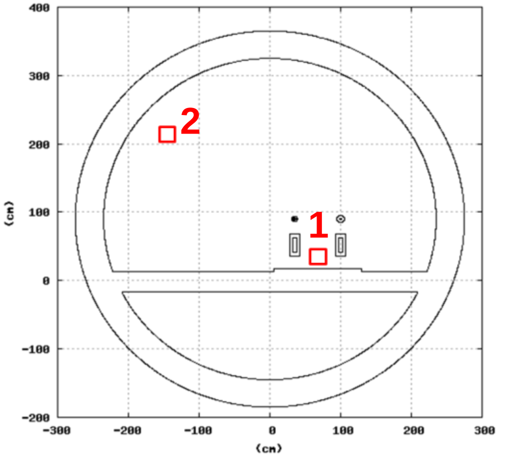
Thank you for your attention

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