BEAM LOSS MONITORING FOR CLIC

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Outline

- Introduction – General BLM Design Considerations
- Design Considerations for CLIC
  - CLIC Machine Protection
  - Loss Limits (2 Beam modules)
- BLM Requirements for CLIC
  - FLUKA Simulations for 2 beam modules (Ionization Chambers)
  - CDR Summary
- Post CDR Phase
  - Alternative Technologies
  - Suitability of Cherenkov Fibers

Introduction – *Design Considerations*

General Design Considerations for BLM System

- Machine Protection system, Beam Diagnostics purposes
- Identify **Failure Scenarios** (misalignment, kicker failure)
- Identify Particle Loss Scenarios in **standard operation**
- **Machine Protection Strategy** (passive protection, BLM to detect onset of failures)
- **Limiting Conditions**
  - Single Shot (damage to equipment)
  - Continuous (damage to beamline components, activation, beam dynamics considerations, damage to electronics) - also monitored by other systems
- **Simulate loss scenarios**
- **Choice of Detector** (meets requirements based on above, consider also cost)

BLM Considerations for CLIC

CLIC Specific BLM Considerations

- Destructive limit - Power density of beam (not energy, power)
- Main Beam (MB) is 10000 * safe beam (M.Jonker)
- Passive and active protection systems required
- Machine Protection Strategy based on "**next cycle permit**"
- Primary role of the BLM system for two beam modules is to detect potentially dangerous beam instabilities and prevent subsequent injection into the Main Beam linac and the Drive Beam decelerators
- CLIC at 100Hz → Response time 8ms (except damping rings) to allow post pulse analysis
- Position Resolution – based on quadrupole (QP) spacing. Minimum QP spacing ~ 1m (2 beam modules)

Loss Limits for CLIC - *failure scenario*

Failure Scenario Loss Limits – Two Beam Modules

- Possible failure scenarios in two beam modules under investigation (C. Maidana)
- → Consider limits based on “Safe Beam” for fraction of beam hitting single aperture
- Main Beam (end of main linac) 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

Loss Limits for CLIC - *operational*

Operation Loss Limits – Two Beam Modules

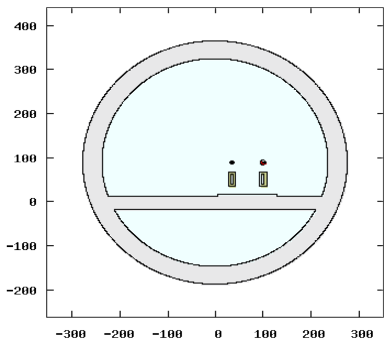
- **Beam Dynamics Considerations** *(Two Beam Modules) – Loss of ~10^{-3} of full intensity of the MB beam over 20km linac, or ~10^{-3} of full intensity of the DB over 875m DB decelerator) result in luminosity losses due to beam loading variations D.Schulte*
- **Activation** (Access issues) *Current estimates of residual dose rates based on FLUKA simulations of beam loss in two beam modules - acceptable at beam dynamics limits* (S.Mallows, T.Otto)
- **Damage to beamline components** *(consider absorbed dose to QP epoxy resin) acceptable at beam dynamics limits*
- **Damage to electronics** *simulations unshielded - limits lower than imposed by beam dynamics limits. However - unachievable loss limit – shielding studies required*

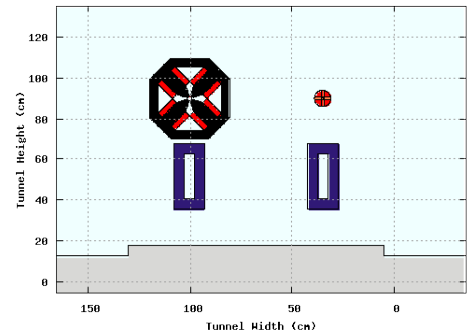
FLUKA Simulations - *CDR*

FLUKA Simulations – CDR – Ionization Chambers

Simulation Settings

- Simulate **loss scenarios** using Monte Carlo Transport Code FLUKA
- Model includes tunnel, floor beam line components and silicon carbide girders





- Losses represented by electrons travelling in direction of beam, generated in circular distribution just inside PETS/AS before QP
- Losses at maximum and minimum energies for DB & MB
  → DB at 2.4 GeV, 0.24 GeV, MB at 1500 GeV, 9 GeV

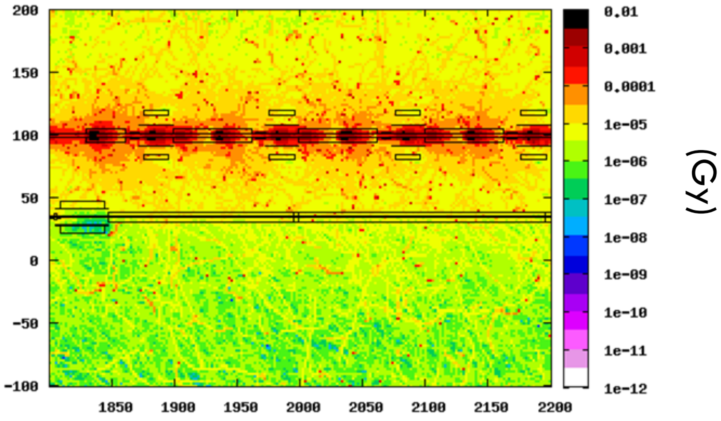
FLUKA Simulations - *CDR*

Dynamic Range – Lower Limits

Sensitivity

- Should detect onset of beam losses leading to beam loading variations – at 1% of loss limit (10^{-5} bunch train distributed over MB linac, DB decelerator)
- FLUKA: Losses distributed along the aperture at the end of every PETS/AS (aperture restrictions)

Example: Spatial distribution of absorbed dose for maximum operational losses distributed along aperture (DB 2.4 GeV)



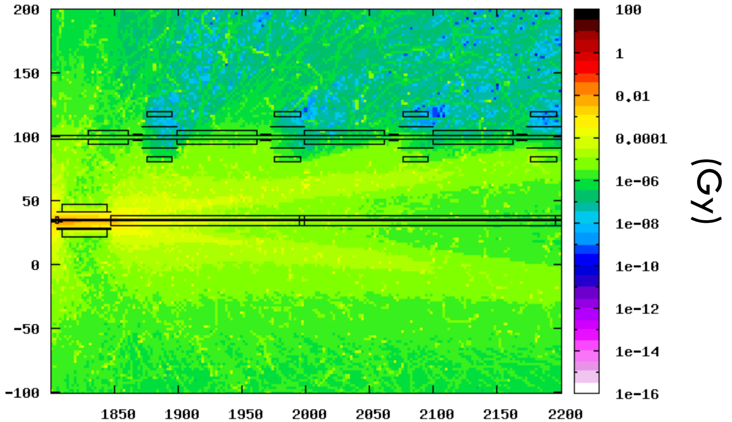
FLUKA Simulations - *CDR*

Dynamic Range – Upper Limits

Dangerous Losses

- Should detect onset of dangerous losses, (& ideally allow for post mortem analysis). 10% of dangerous limits.
- Dangerous loss: 1.0% DB bunch train, 0.01% bunch train MB
- FLUKA: Loss at single aperture at the end of a PETS /AS before a QP

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

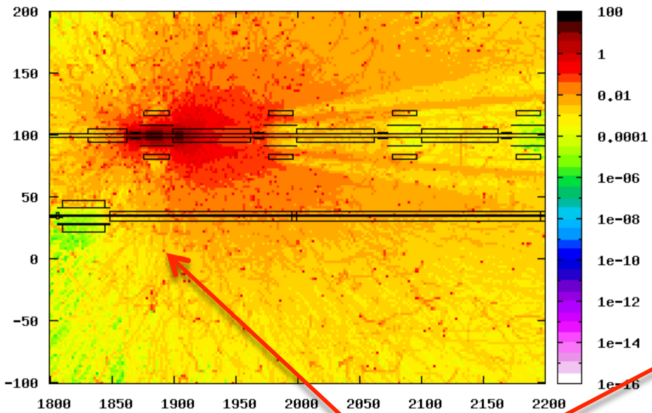


FLUKA Simulations - *CDR*

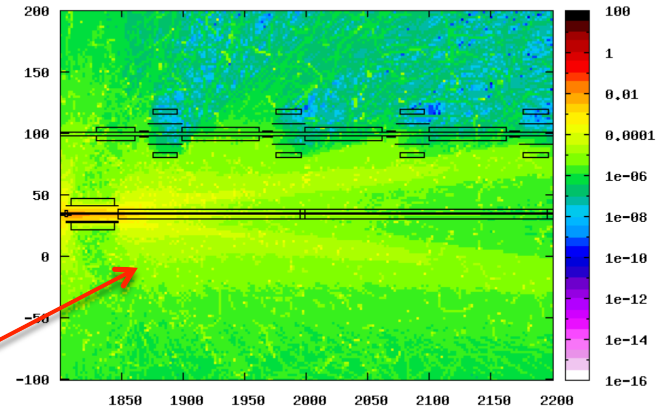
Cross Talk Issues

- Desirable to distinguish between a failure loss from each of the beams

Destructive DB 1.0% of bunch train hits single aperture restriction



Destructive MB 0.01% of bunch train hits single aperture restriction



Spatial Distribution of prompt Absorbed Dose (Gy) resulting from FLUKA Simulation of dangerous loss at single aperture restriction for the 2.4 GeV Drive Beam (left), 9 GeV Main Beam (right)

- Loss of 1.0% in DB provokes similar signal as a loss of 0.01% of MB in region close to MB quadrupole.
- Due to a different time structures of the two trains, a detector with adequate time resolution could be used distinguish losses from either beam
- Not a Machine Protection Issue – Dangerous loss would never go unnoticed

Requirements - *Summary Table*

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*

- *Ionization Chambers fulfill necessary requirements for a machine protection system (except MB Damping Rings – where Cherenkov Radiators + PMT recommended, as baseline technology choice)*

- *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*

Alternative Technologies – *Summary Table*

- Detectors that cover large distance along beamline, optical fibers, long ionization chambers
- Optical Fibers – Scintillating fibers give about 1000 times more light output. Cherenkov Fibers are more radiation hard. Withstand ~ 30×10^7 Gy, whereas scintillating fibers see a reduction of light output at ~ 1 MGy

	Dynamic Range	**Sensitivity (nC/Gy)**	**Response Time**	**Position Resolution (longitudinal)**
Long Ionization Chambers ***(FERMILAB Ar + CO_2)***	10^4 (SLAC)	2.10^2cm^{-1} (FERMILAB)	~ μ s	m-km
Cherenkov Fibers (with SiPM) (A.Intermite Liverpool Uni.)	~10^4	(10^5cm^{-2})	~50 ns	~20cm
Plastic Scintillating Fibers (with PMT)	<10^7	<10^8cm^{-2}	~10 ns	m

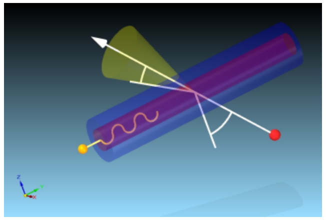
Cherenkov Fibers as BLMs

Cherenkov Signal in an Optical Fiber

Cherenkov Radiation

- Cherenkov radiation emitted when a charged particle enters the fiber with v>c produces photons along Cherenkov cone of opening angle

$$\cos\theta = \frac{1}{n\beta}$$



Two Considerations

- **Number of Photons** generated in fiber by charged particle

$$\frac{d^2 N_{ph}}{d\lambda dL} = \frac{2\pi\alpha z^2 \cdot \sin^2\theta}{\lambda^2}$$

Blue Light Dominates

- **Proportion** of photons **transmitted,** Cerenkov Efficiency

$$CE \propto \cos^{-1}\left[\frac{\beta\sqrt{n^2 - NA} - \cos\varphi_e}{\sin\varphi_e\sqrt{\beta^2 n^2 - 1}}\right]$$

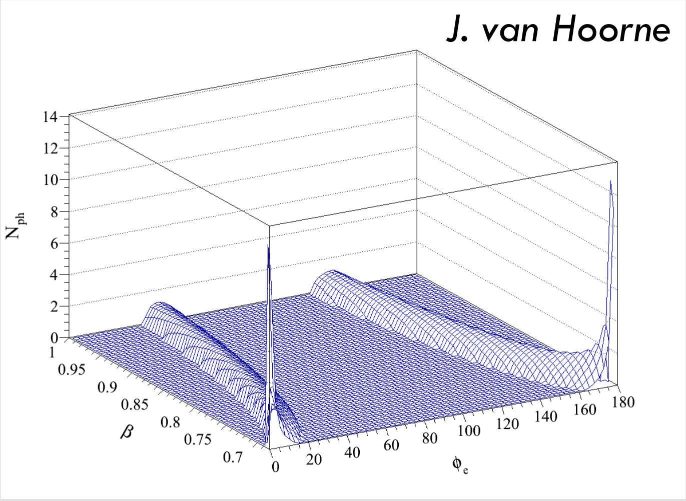
Angular dependency

Where $\boldsymbol{\Phi_e}$ *is the angle between the incoming radiation and the fiber axis,*
NA is the 'numerical aperture' of the fiber $NA = \sqrt{n_{core}^2 - n_{clad}^2}$

Cherenkov Fibers as BLMs

- For a given fiber diameter and NA, expected number of **transmitted** photons as a function of the particle velocity and angle with respect to the fiber axis, ϕ_e can be calculated

- Number of **transmitted photons** per **charged particle** crossing the fiber as a function of β and ϕ_e for a fiber of 0.365 mm diameter and NA = .22



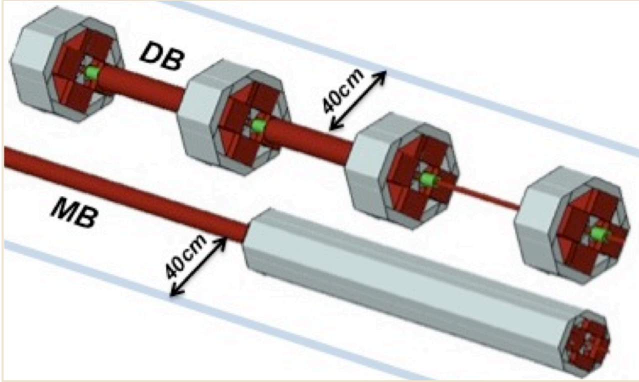
- FLUKA/GEANT4 can also simulate the production and transport of Cherenkov photons
- Calculation checked with FLUKA (simple study – electron beam at a fiber (angle 0-90deg))

FLUKA Simulations – *Cherenkov Fibers*

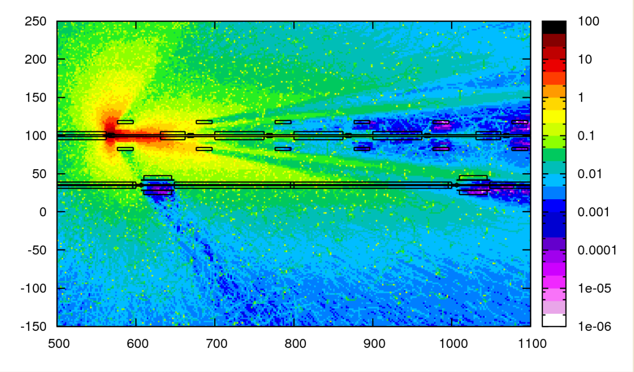
First calculations for IPAC 2011

FLUKA Settings (updates since "CDR" simulations):

- Removed tunnel wall/floor (CPU time)
- Implemented representation of aperture restriction into FLUKA geometry
- Failure loss scenario - beam directed on aperture at maximum geometrical angle permitted between focusing and defocusing QP
- Score angular and velocity distribution of charged particles at possible fiber locations
- Binned angular distribution and velocities of charged particles with respect to boundary (5cm high, 40cm from beamline, parallel to beamline)



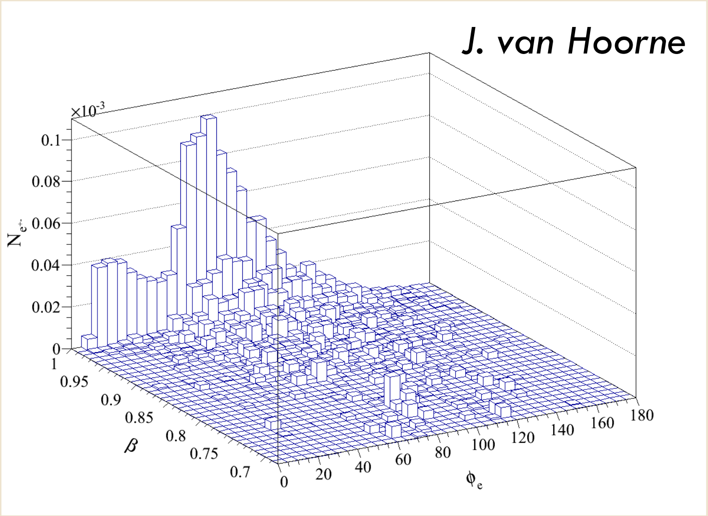
Blue lines indicate location of boundaries



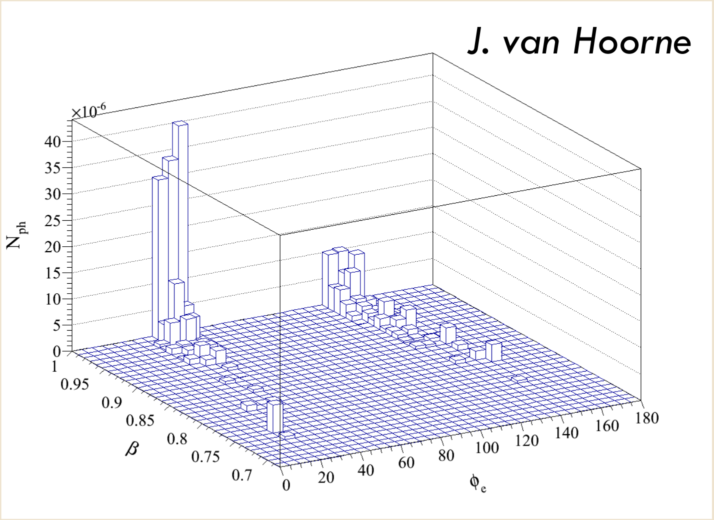
Spatial Distribution of absorbed dose - DB loss at 2.4 GeV

FLUKA Simulations – *Cherenkov Fibers*

Results



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



Transmitted photon distribution, normalized to one lost beam electron, for single loss at 2.4 GeV in the DB.

- Not all of the charged particles crossing the fiber above the Cherenkov threshold generate transmitted photons

FLUKA Simulations – *Cherenkov Fibers*

Sensitivity and Dynamic Range Requirements

- *Based on loss limits (as before)*
- *Expressed in terms of photons produced in fiber*
- *Sensitivity and dynamic range requirements for a downstream photodetector allows the use of Silicon Photomultipliers (SiPM) - 100m fiber!*
- *Attenuation not considered. The attenuation coefficient (fiber) is proportional to λ^{-4}. Therefore, for fibers longer than 200m the blue/green part of the radiation spectrum becomes insignificant*
- *Larger diameter fiber maybe needed for increased photon production*

	Sensitivity* (N_{ph}/train)	Dynamic Range
DB 0.24 GeV	$5 \cdot 10^2$	$5 \cdot 10^4$
DB 2.4 GeV	$5 \cdot 10^3$	$2 \cdot 10^4$
MB 9 GeV	$4 \cdot 10^1$	$1 \cdot 10^3$
MB 1.5 TeV	$8 \cdot 10^2$	$5 \cdot 10^3$

Arrival duration of the photons 410 ns (DB) and 323 ns (MB) (100m fiber)

Summary

- *A method has been developed to determine the Cherenkov signal in fibers at the CLIC two beam test modules*
- *Cherenkov fibers seem to be a suitable candidate for a BLM system in terms of dynamic range, sensitivity, temporal and spatial resolution*
- *Cherenkov fibers will be installed in the CLIC Test Facility (CTF3) in the next year to further test the feasibility of a Cherenkov fiber system*

Outlook

Short Term

Cherenkov Fibers BLM System

- Choice of photodetectors: Considerations - SiPMs are cheap, radiation hard, require low operating voltage (<100V). Dynamic range limited by number of pixels, etc. etc.
- Characterize fibers at a test beam facilities
  Use both standard PMTs and SiPMs. Test:
  - **photon yield** depending on the **diameter of the fiber** core
  - **photon yield** depending on the **incident angle** beam w.r.t .fiber axis
- First Installation at **CTF3/CLEX** (details to be confirmed)
  - Cherenkov signal and the **time resolution** which can be achieved with standard PM and borrowed (L Froehlich, INFN), or O.T.S SIPM + frontend electronics
  - Cross talks issues at TBTS

Outlook

Short Term

Simulations

- Cherenkov Fibers Simulations (Improve/expand on study)
- Photons travelling in fiber upstream direction
- Keep up to date with loss scenarios/limits (M. Jonker)
- Cross Checks FLUKA/GEANT 4/calculation from theory with experimental data for photon production and transport

Long Term

- Cross Talk Issues (between beams)
- Investigate other radiation sources (DB decelerator dumps, RF cavities), turn-arounds, etc
- Investigation and simulation of loss scenarios in other machine parts DB combiner rings, turn-arounds, MB damping rings
- Investigate other technologies (Long Ionization Chambers)

The End

Thank you for your attention!

DB/MB Parameters

	Energy [GeV]	Train duration [ns]	e^{-}/train	Rep Rate [Hz]
DB	2.4-0.24	243.7	$1.54 \cdot 10^{14}$	50
MB	9-1500	156	$1.16 \cdot 10^{12}$	50