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Loss simulations: Status, requirements for next version.

Contents

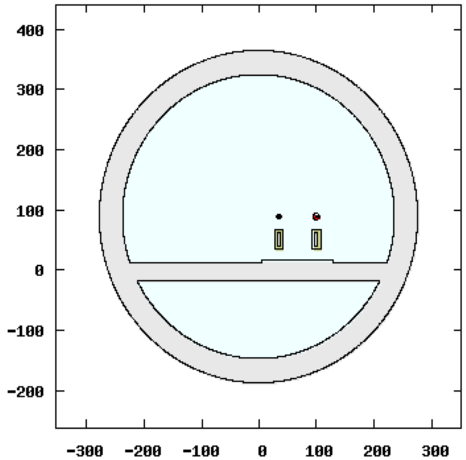
- Loss Simulations (Made in 2010) for Radiation Protection/Damage "CDR PHASE"
- Loss Simulations for Beam Loss Monitoring
  - CDR Ionization Chambers (2010)
  - "Post" CDR phase (2011)
- Discussion and Requirements for Next Version (Time Scales/ Person Responsible)
  - Losses: rescaling of results
  - Scenario/geometry/material Updates: re-simulation

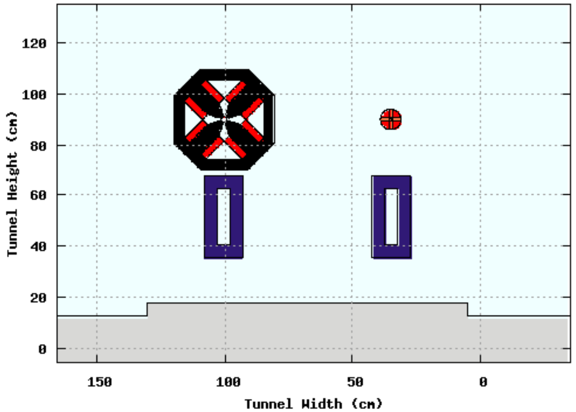
Operational Loss Limits

- Loss Limit (what we have understand so far):
  - **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*
  - However it is also unlikely that they will be able to operate losing much less. Therefore this must define the loss limits. (activation, damage to electronics must be compatible with these limits)

Fluka Simulations 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

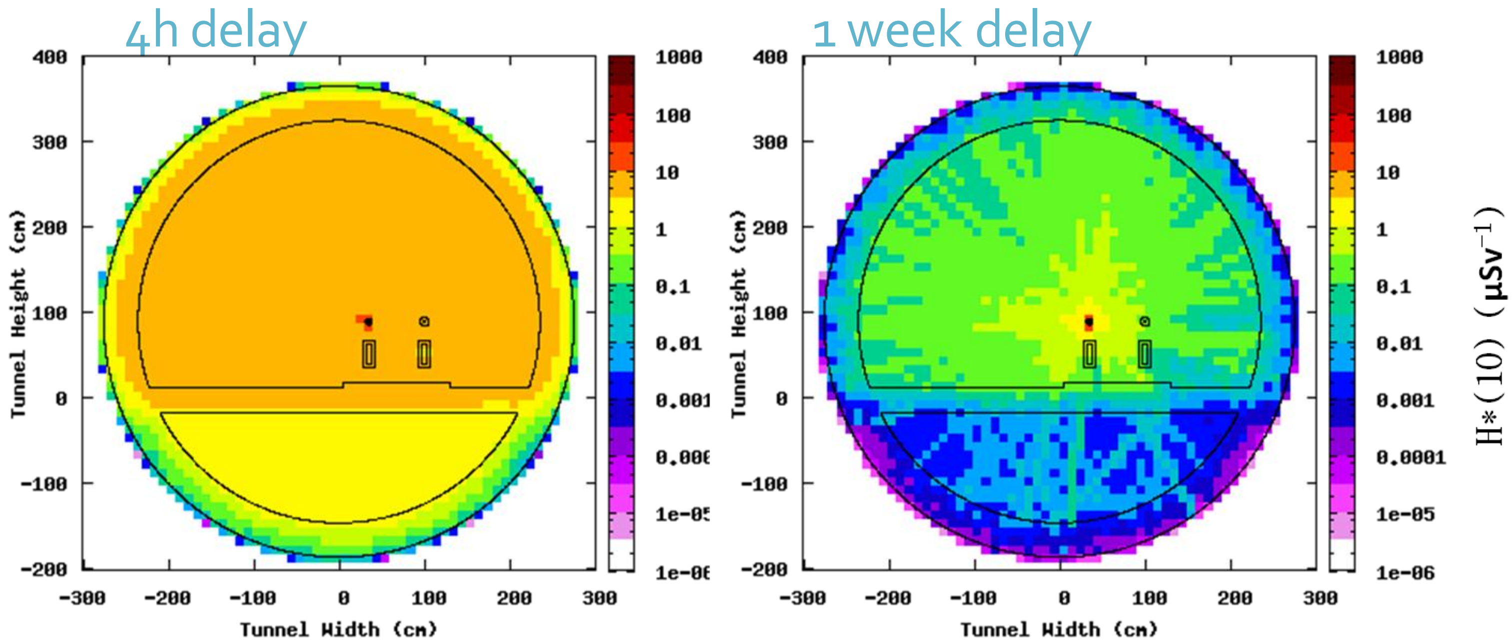
Fluka Simulations Settings

- Loss Scenario "operational" (used for Dose Rates, Fluences associated with damage to electronics,)
  - MB: Loss distributed continuously along aperture (aperture restrictions at end of every AS (8*ASs per module))
  - DB: Loss distributed regularly at the end of every PETS (location of aperture restrictions)

- SCORE (in tunnel)
  - **Residual Ambient Dose Rates** at Cooling times 4h, 1 day, 1 week (Irradiation profile of 11 year cycle, 180 days operation, 185 days shutdown) →Access Issues?
  - **1 MeV neutron equivalent fluence , >20MeV hadron fluence , Absorbed dose** → Shielding required ?
  - **Absorbed Dose near beam line** → BLM signal (Ionization chambers)

Results - Ambient dose rates

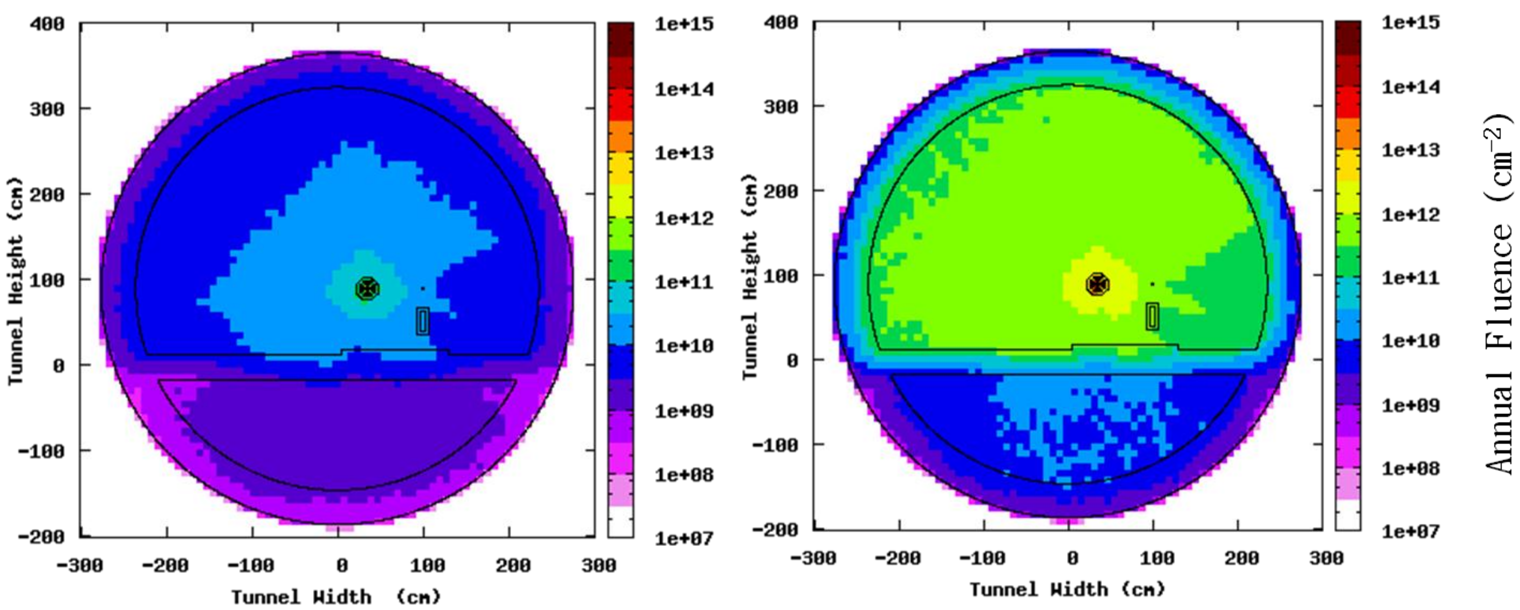
- Ambient dose rate map in a plane orthogonal to the beam at the high-energy end of CLIC (*E*=1.5 TeV) after 1 year of exploitation at nominal beam intensity and an average beam loss of 5 10^{-8} m^{-1}. Ambient dose rate is evaluated for different delay times after turning off the accelerator.



SCALING! Losses of 5 *10^{-8} m^{-1} (180 d continuous running)

Results - ‘Electronics Damage’ 1MeV neutron equivalent fluence

- LEFT: Distribution of the 1MeV neutron equivalent fluence in the tunnel cross section for beam loss in the main beam at 1500 GeV.
- RIGHT: Distribution of the energetic hadron fluence in the tunnel cross section for beam loss in the main beam at 1500 GeV.

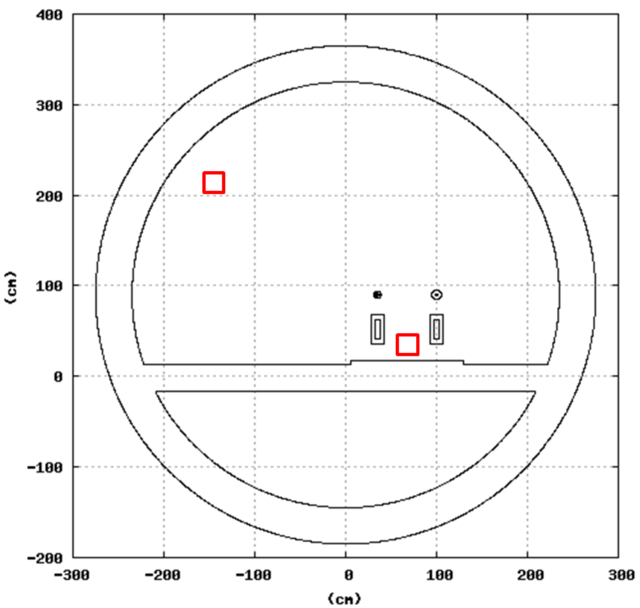


SCALING! Losses of $5 * 10^{-8}$ m^{-1} (180 d continuous running)

Results " Electronics Damage"

- **Summary Tables**
- Estimated 1 MeV neutron Equivalent Fluence in 2 tunnel locations for losses from the Drive Beam (DB) and Main Beam (MB).
- Estimated High Energy hadron fluence in 2 tunnel locations for losses from the Drive Beam (DB) and Main Beam (MB) assuming maximum losses permitted by beam dynamics considerations.

SCALING! Main Beam: $5 * 10^{-8}\ m^{-1}$ Drive Beam $1.25 * 10^{-6}\ m^{-1}$



	1-MeV neutron eq. fluence Close to accelerator (cm^{-2} $year^{-1}$)	1-MeV neutron eq. fluence Close to tunnel wall (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

	>20MeV hadron fluence Close to accelerator (cm^{-2} $year^{-1}$)	**>20MeV hadron fluence Close to tunnel wall (cm^{-2} $year^{-1}$)**
DB – 240 MeV	1.0e9	2.3e8
DB - 2.4 GeV	6.5e10	1.6e10
MB – 9 GeV	2.3e8	6.1e7
MB – 1500 GeV	2.4e10	7.0e9

Damage to Electronics Tolerable Levels

- Radiation damage mechanisms and tolerable levels leading to negligible damage of accelerator components or electronics

Damage Mechanism	Relevant Estimator	Tolerable Levels
Material Damage	Total Ionizing Dose (Absorbed Dose)	<1Gy /year (COTS) <1MGy /year (epoxy resin, QP coils)
Lattice Displacement	Non ionizing energy loss scaled to "1 MeV neutron Equivalent Fluence" *	$<1\text{x}10^{8}\text{cm}^{-2}$ /year (COTs)
SEEs	>20MeV Hadron Fluence	$<1\text{x}10^{7}\text{cm}^{-2}$ /year** (COTs)

- **Non ionizing energy loss (NIEL) is usually scaled for convenience to the NIEL of 1 MeV neutrons where any particle fluence with a specific energy distribution is expressed in terms of the '1 MeV neutron-equivalent fluence' producing the same bulk damage in a specific semiconductor.*

***For SEE's only the probability of failures can be determined, electronics started to fail due to SEE's at high energy hadron fluencies of $1\text{x}10^{7}\text{cm}^{-2}$ at CNGS*

Damage to Epoxy Resin

- **Estimated fractional beam loss required to accumulate an absorbed dose of 1 MGy per year in quadrupole magnet coils (assume limit of 10MGy over lifetime)**
- **NB Loss Scenario: Loss represented just before QP!!**

	Loss point	**Fractional Beam Loss per QP – for 1 MGy/yr in coils**	**Fractional Beam loss (m^{-1}) for 1 MGy/yr in coils**
DB – 240 MeV	End of PET (before QP)	$2.1\ 10^{-6}$	$2.1\ 10^{-6}$
DB - 2.4 GeV	End of PET (before QP)	$2.0\ 10^{-5}$	$2.0\ 10^{-5}$
MB – 9 GeV	End of AS (before QP)	$4.8\ 10^{-5}$	$1.2\ 10^{-5}$
MB – 1500 GeV	Continuous in AS (1m before QP)	$4.3\ 10^{-7}$	$2.4\ 10^{-10}$

However, Simulations- just before QP. MB high energy QP spacing 18m

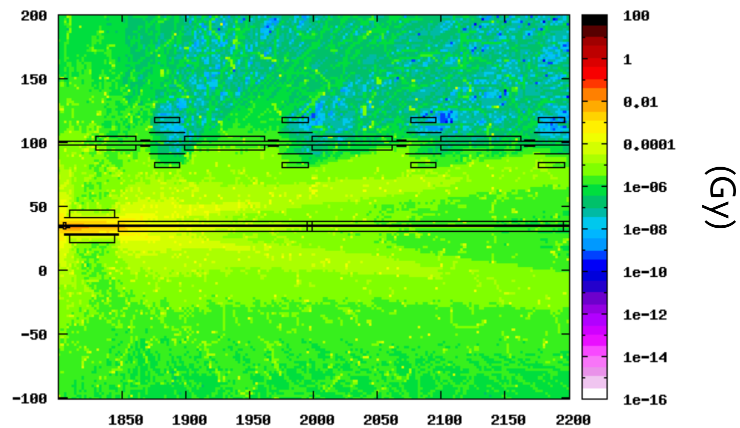
Limits , beam dynamics: Main Beam: 5 $*10^{-8}$ m^{-1} Drive Beam 1.25* 10^{-6} m^{-1}

BLM Requirements Ionization Chambers

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 1.53e12 electrons, 0.01% bunch train MB 1.16e8 electrons
  - 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

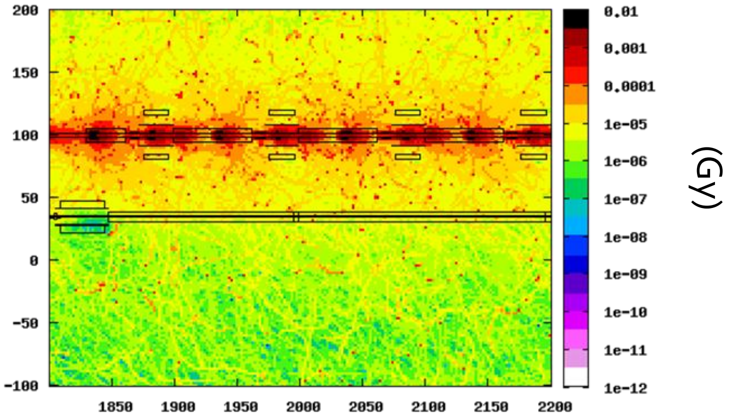


BLM Requirements Ionization Chambers

Dynamic Range – Lower Limits

- Sensitivity requirement:
  - **FLUKA Loss Scenario**: Losses distributed regularly along the vacuum chamber at the end of every PETS (DB) or AS (MB)
  - **Scaling**: 0.01 × loss limit for beam loading variations (to detect onset of such losses) = 10^{-5} bunch train distributed over MB linac, DB decelerator)

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



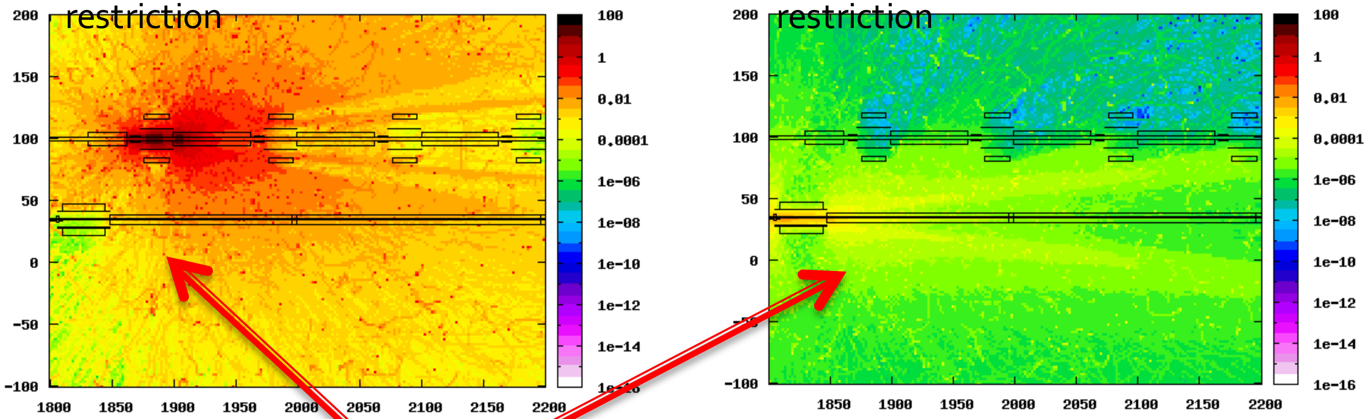
BLM Requirements Ionization Chambers

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 - CDR *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*

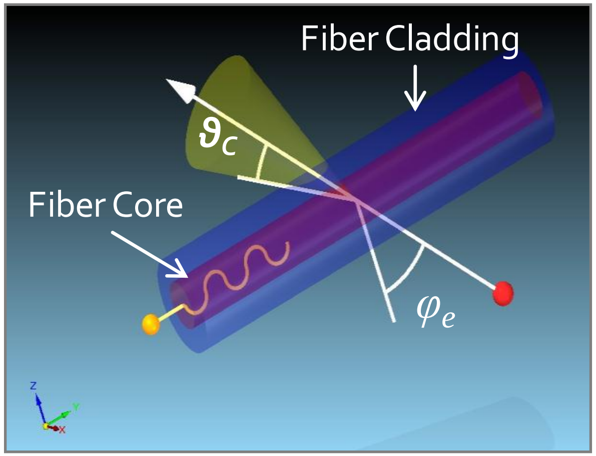
Cherenkov Fibers

Cherenkov Signal in an Optical Fiber

Cherenkov Radiation

- When a charged particle enters the fiber with v>c it produces photons along Cherenkov cone of opening angle

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



Need to Consider Both:

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

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

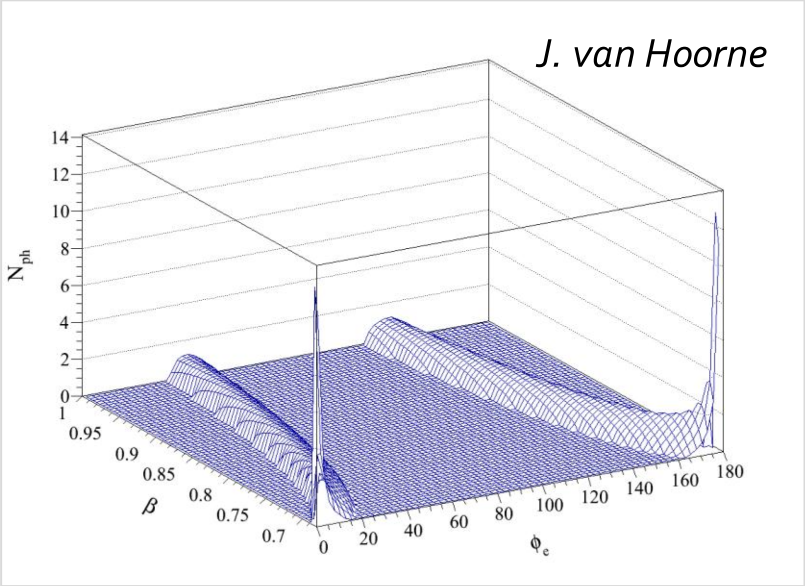
- The **Proportion of photons transmitted,** Cerenkov Efficiency

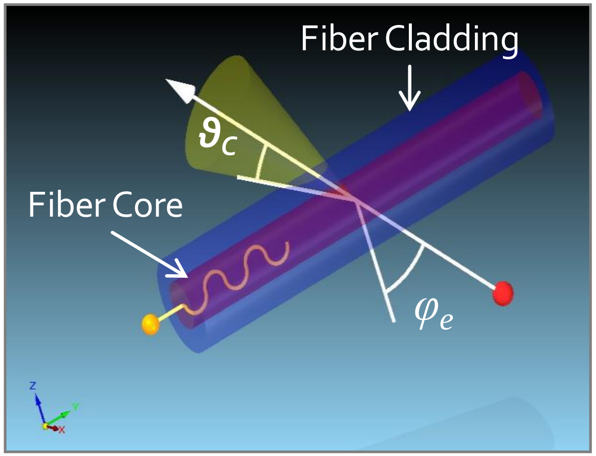
$$CE \propto \cos^{-1}\left[\frac{\beta\sqrt{n^2 - NA} - \cos\varphi_e}{\sin\varphi_e\sqrt{\beta^2 n^2 - 1}}\right]$$

NA is the 'numerical aperture' of the fiber

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

Cherenkov Fibers





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**

NA is the 'numerical aperture' of the fiber

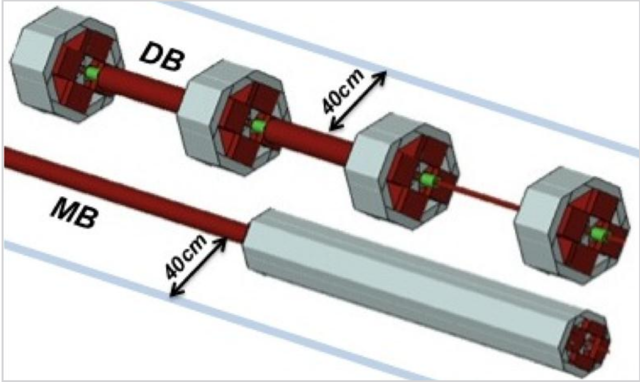
$$NA = \sqrt{n_{core}^2 - n_{clad}^2}$$

FLUKA Simulations 2011 – *Cherenkov Fibers*

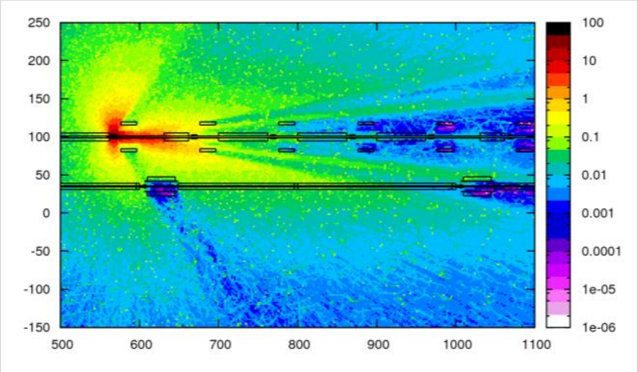
First calculations to determine CherenkovSignal

FLUKA Settings (updates):

- 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)



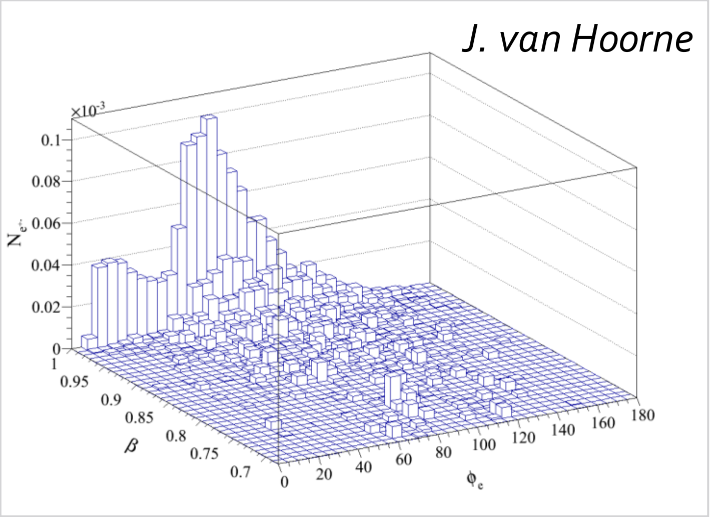
Blue lines indicate location of boundaries



Spatial Distribution of absorbed dose - DB loss at 2.4 GeV

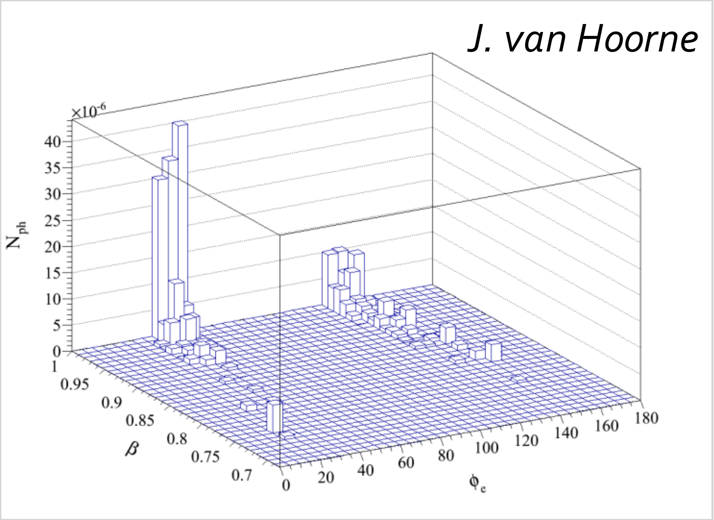
FLUKA Simulations – *Cherenkov Fibers*

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



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 or 'trapped' photons

FLUKA Simulations – *Cherenkov Fibers*

Sensitivity and Dynamic Range Requirements

- *Based on loss limits (as before)*
- *Dynamic Range based on of rate of arrival of photons*
- *Sensitivity and dynamic range requirements for a downstream photodetector allows the use of Silicon Photomultipliers (SiPM) - 100m fiber!*
- *Larger diameter fiber can be used 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)

Simulations - Conclusions

- *RP calculations – ambient dose rates seem high Normalization OKAY !- was double checked (September 2010), T.Otto, S Mallows Make repeat simulations with simplified geometry (Sophie)* Sophie
- *Damage to epoxy resin loss distribution ? Normalization OKAY. Results (stats) MB 1.5TeV to be checked. Requires a clearer way of presenting?* Sophie
- *SCALING – How would a loss of the 10^{-3} fraction of intensity actually be distributed along the aperture? This would affect* Everyone
  - *BLM sensitivity requirements*
  - *All radiation related results*

Simulations - Conclusions

To Do (RP, Rad Damage)

- **A calculation of the radiological conditions at the shaft bottoms** is required to see if (and under what conditions) these areas are accessible during operation (The tunnel being blocked by movable shielding).

- The radiation maps in the tunnel have to be refined to find optimum position for electronics with respect to beam line and possibly to profit from shielding effects of the decelerator quadruples.
Simulations with shielding for electronics (Fe, Concrete)

J. Vollaire + Tech student?

- The materials envisaged to be used in the clic machine has to be reviewed to see if these contain elements that may have radiological consequences. Include in Simulations