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How to monitor the beam?
Beam Loss Monitors

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Outline

- BLM: goals and top-level requirements
- BLM detectors: locations, types
- Conceptual design for the BLMs in the Superconducting parts of the linac
- Summary

BLM: goals and requirements

- BLM goals:
  - Primary goal: **protection** - detect abnormal beam behaviour.
  - In addition: **monitoring** - provide the means to monitor the beam losses during the normal operation.
- BLM requirements:
  - Protection functionality requires us to know what are we protecting - **list of beam loss scenarios** to which BLM should react - translates to setting the **thresholds** and **measurement time constants**.
  - Protection functionality gives a constraint on the system's shortest **response time** and sets the upper limit of the system's **dynamic range**.
  - Monitoring functionality sets the lower limit on the system's dynamic range.

Response time

- Response time requested by machine protection [1]:
  - In Normal Conducting (NC) linac: ~1 μs.
  - In Superconducting (SC) Linac: ~10 μs.
  - Numbers based on a simplified melting time calculations [2].

- Rechecked the calculations with updated parameters (details under Backup material)
  - **NC linac:** the calculations imply that we should be even faster than 1μs. But:
    - Note that these are simplified calculation that give a conservative result on melting times: no cooling included, conductive cooling might be efficient for a thin layer [3] – a realistic option for this case.
    - Calculations are focused on worst case scenario with full focused beam at perpendicular incidence – only realistic scenario where valve enters the beam - The primary layer of protection for this case is expected to be the Local Protection System.
  - **SC linac**: the 10μs requirement for response time fits well with these calculations
    - However, experience at SNS raises a **concern**.
    - Degradation of cavities observed at SNS after loosing <15μs pulse of 26mA beam ~10/day [4].
    - Do we need to be faster in order to detect this type of events in time?

Dynamic range, thresholds & time constants (1/2)

- Dynamic range
  - Needs to be determined in order to select suitable FE electronics
  - Preliminary values have been set in the past
    - "BLM is required to be able to measure at least 1% of 1W/m loss during normal. operation and up to 1% of the total beam loss" - gave an estimation on input FE current range 800nA – few mA for the BLMs in SC linac.
    - Needs a revision due to the lack of inputs at the time.

- Measurement time constants
  - Preliminary list of measuring time constants (see p.16) based on the expected beam modes.
  - Need to correlate with time constants of the components that can fail.

- Thresholds
  - More detailed inputs needed to be able to addressed this issue.

Dynamic range, thresholds & time constants (2/2)

- Required inputs to determine these values:
  - List of **beam modes**: exists [5]
  - Complete list of possible **beam loss scenarios** (due to either mechanical or accelerator elements) with time constants, also need to know what are we protecting and the damage levels (also the quench levels for cavities).
  - Loss scenarios where **single component** (either RF cavity or quadrupole) fails "instantly" have recently been studied [6] and give a good starting point for BLM studies, however this does not give a complete picture (due to several reasons).
  - **Concern**: bad steering due to a human error could cause more localized losses - need to know what is the beam failure scenario which gives most focused beam hitting the beam pipe/accelerator component at least shallow angle.

- Once we have complete list of accident scenarios and loss maps of beam failures, Monte Carlo codes can be used to:
  - Refine the dynamic range and placements of detectors.
  - Determine the thresholds, investigate options to react on information from more than 1 detector.
- Plan to (re)address these topics in the near future

BLM detectors: locations

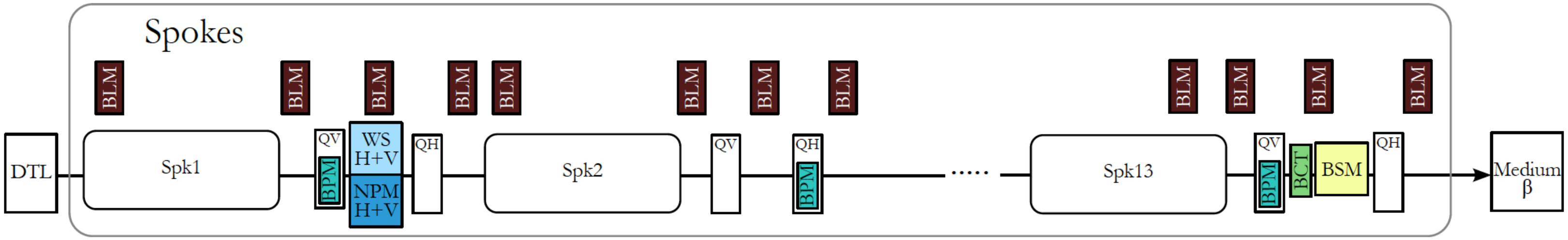
NC linac:

- 1-2 devices per m or 1/m depending on technology.

SC linac:

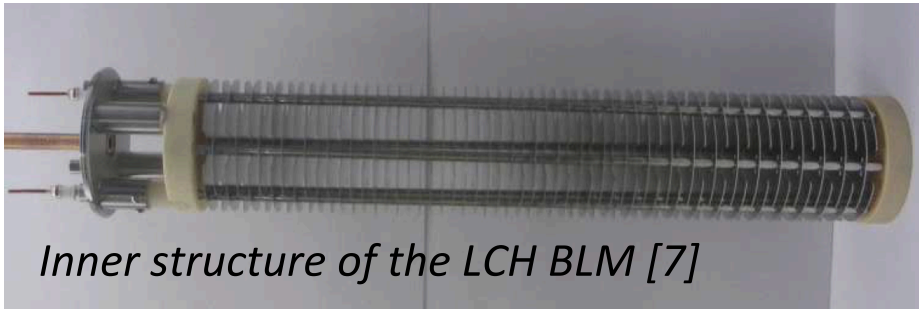
- 3-4 devices per doublet lattice cell: 4 where there is a cryomodule and 3 in the transport section.
- More exact positions under investigation by PhD student M. Jarosz.
  - MARS MC simulations combined with heuristic optimisation methods.
  - Due to the absence of loss scenarios a number of discrete point losses along the beam pipe is assumed.

Linac section	**Num. of devices**	
	IC	**ND**
RFQ	/	(1-2/m) 6
MEBT	/	(1-2/m) 4
DTL	(1/tank) 5	(1-2/m) 17
Σ	5	27
Spokes	13×4=52	/
Medium β	9×4=36	/
High β	21×4=84	/
HEBT	(3/q-pair) 15×3=45	/
dog leg	(3/q-pair) 7×3=21	/
	(1/dipol) 2	/
A2T	15	/
Dump line	6	/
Σ	261	/
ΣΣ	266	27
ΣΣΣ		293



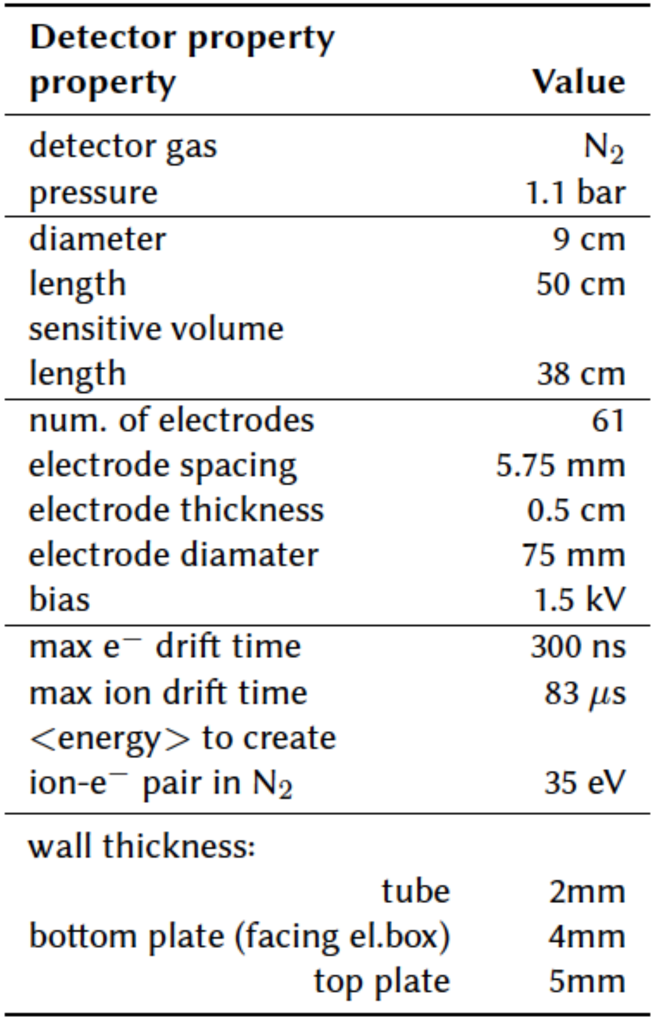
BLM detectors: SCL

- Showers of secondary particles (charged and neutral) are expected in SC linac.
- Parallel plate gas Ionisation Chambers (ICs) developed for the LHC BLM system will be used – chosen due to their fast response.
- ICs ordered in Summer 2014 (production line setup in Russia, to replenish spares for LHC and make prod. series for ESS and FAIR).



Inner structure of the LCH BLM [7]

From [6], [7]



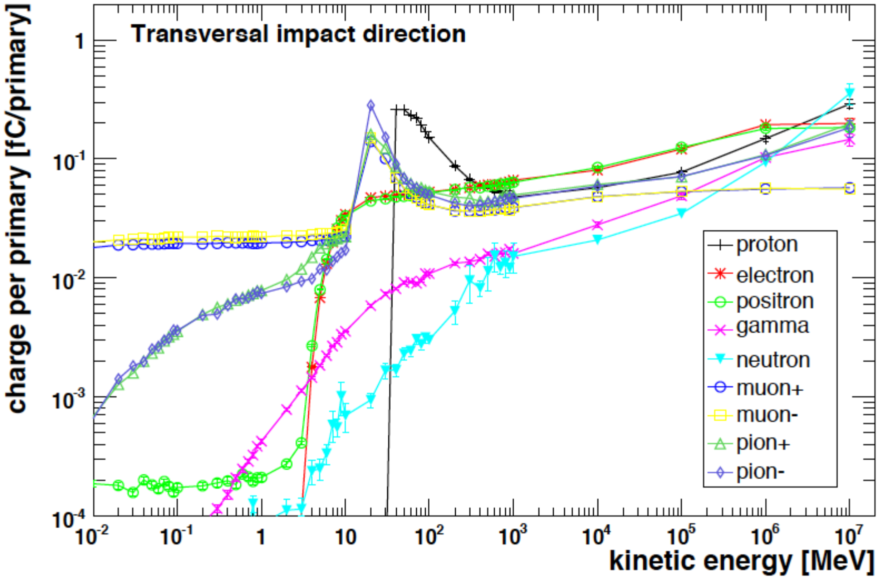
Detector property property	Value
detector gas	N_2
pressure	1.1 bar
diameter	9 cm
length	50 cm
sensitive volume length	38 cm
num. of electrodes	61
electrode spacing	5.75 mm
electrode thickness	0.5 cm
electrode diamater	75 mm
bias	1.5 kV
max e^- drift time	300 ns
max ion drift time	83 μs
<energy> to create ion-e^- pair in N_2	35 eV
wall thickness:	
tube	2mm
bottom plate (facing el.box)	4mm
top plate	5mm

Background due to the cavities (1/4)

What we should consider when using ICs in SCL:

- Photon background due to the RF cavities:
  - Mainly due to field emission from electrons from cavity walls, resulting in bremsstrahlung photons created on cavities/beam pipe materials.
  - Levels are difficult to predict numerically – they depend on the quality of cavities.
  - Energy spectra estimations show that photons up to few tens of MeV can be expected [9].
- ICs are not insensitive to photons:
  - For the LHC ICs the “cut off” for transversal incidence for photons and electrons is below ~2MeV and
  - 30MeV for protons and neutrons [10].

LHC BLM IC response functions [10]



Background due to the cavities (2/4)

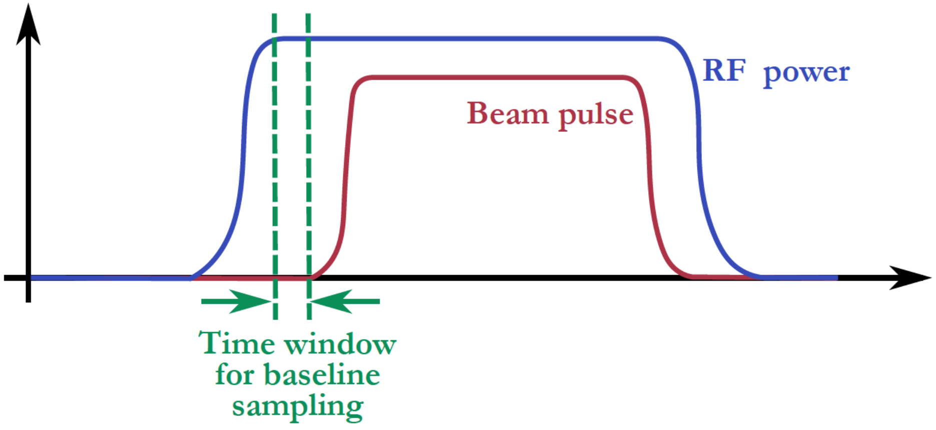
Estimation of the background levels due to the RF:

- Plan to do assess this with tests at the RF test stand in Uppsala (Spokes) and potentially in CEA/Saclay (elliptical).
- The tests can potentially give an upper limit on the RF background level, since:
  - Tests are performed without beam.
  - Tests are probably done with higher RF power than used for normal operation.
  - Less material for "shielding" (magnets,…) is expected.
- However, these tests can not give the full insight, since this background depends on the quality of the cavities and is influenced by beam loading.

Background due to the cavities (3/4)

How can we address this:

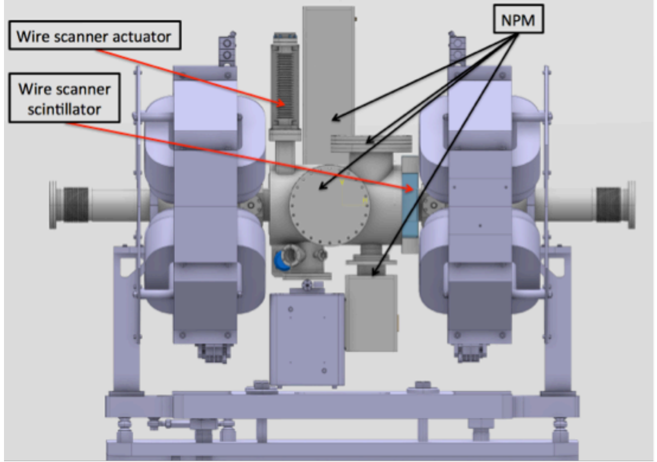
- Plan to do the baseline subtraction (also done at SNS):
  - The background is cavity and time dependent.
  - Need to estimate the baseline for each BLM detector separately.
  - For each pulse we would like to sample the data for the baseline calculation in the time window after the RF is turned on and before the beam pulse arrives in order to correct the thresholds or raw data in the pulse accordingly.

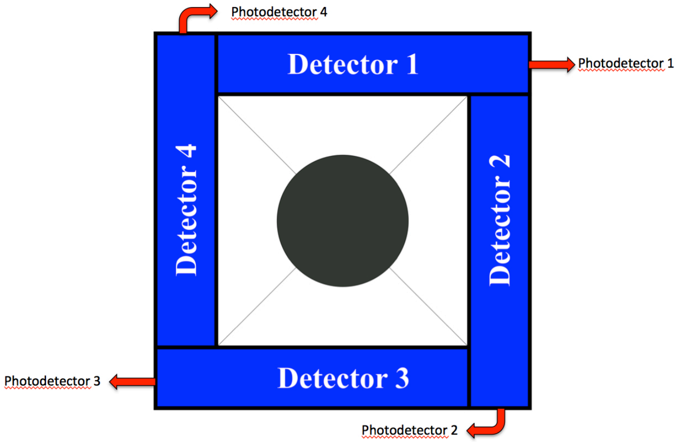


- In addition to ICs we could also use Cherenkov based detectors - not effected by the background due to the RF cavities.

Background due to the cavities (4/4)

- Background from cavities is a concern also for the Wire Scanner (WS) measurements in the Elliptical section.
  - Proposed dual readout based on collecting both the scintillator and Cherenkov photons separately [9] [11].
  - Planned to be used for beam energies above 200MeV, 3 devices in Medium and 1 in High β section.
- For the BLM we would like to make use of the proposed photon based dual readout for the WS:
  - The idea is to use the Cherenkov part of the readout as a BLM during normal operations (when no wire is inserted in the beam).
  - Plan to do series of Monte Carlo simulations to investigate if this is an option for BLM.
  - Depending on the outcome of the study there is a possibility to increase the number of these devices.

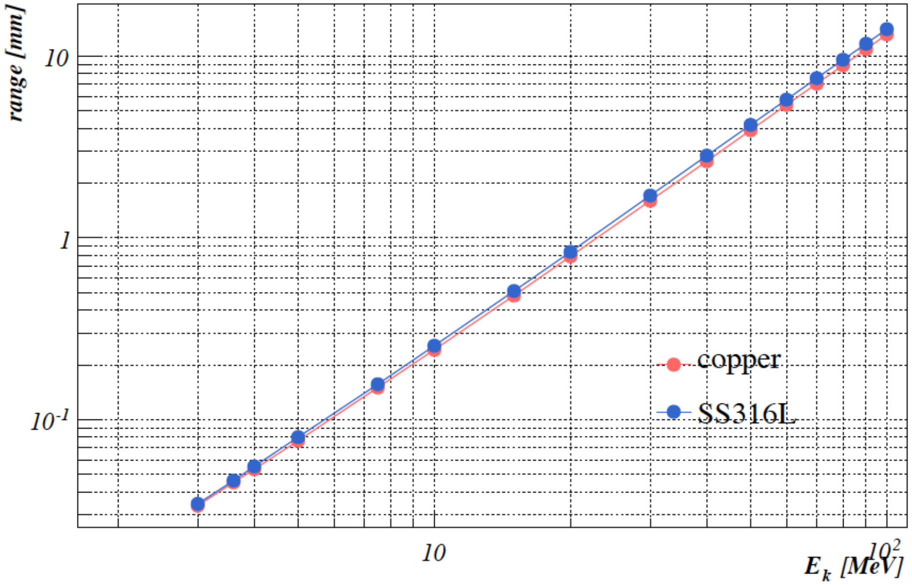




BLM detectors: NC linac (1/2)

- DTL:
  - Tank walls ~3cm stainless steel.
  - Protons (3.6 – 90 MeV) will be stopped in the walls of the tanks.
- Expected particle fields outside of the DTL tanks dominated by neutrons and photons.
- Similar holds for RFQ and MEBT.

Range of protons in copper and SS316L (calculations with SIRM)

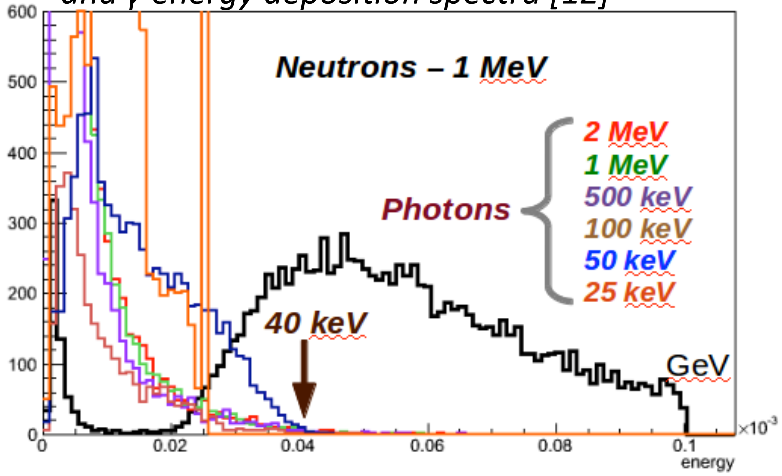


- Currently considering to use micromegas detectors in the low energy part of the linac.
- The idea is to design a micromegas detector sensitive to fast neutrons and “blind” to photons (X- and γ- rays) based on signal discrimination.

BLM detectors: NC linac (2/2)

- On going assessment of the feasibility of such detectors, by the micromegas team from CEA Saclay.
- Series of simplified simulations look promising [12].
- Further simulations are necessary to optimize geometry, material choice and gas configuration for best neutron/photon discrimination.
- Neutron and photon fluxes needed to determine the gain and threshold for optimal photon rejection.

Example of simulated p (from 1MeV n) and γ energy deposition spectra [12]

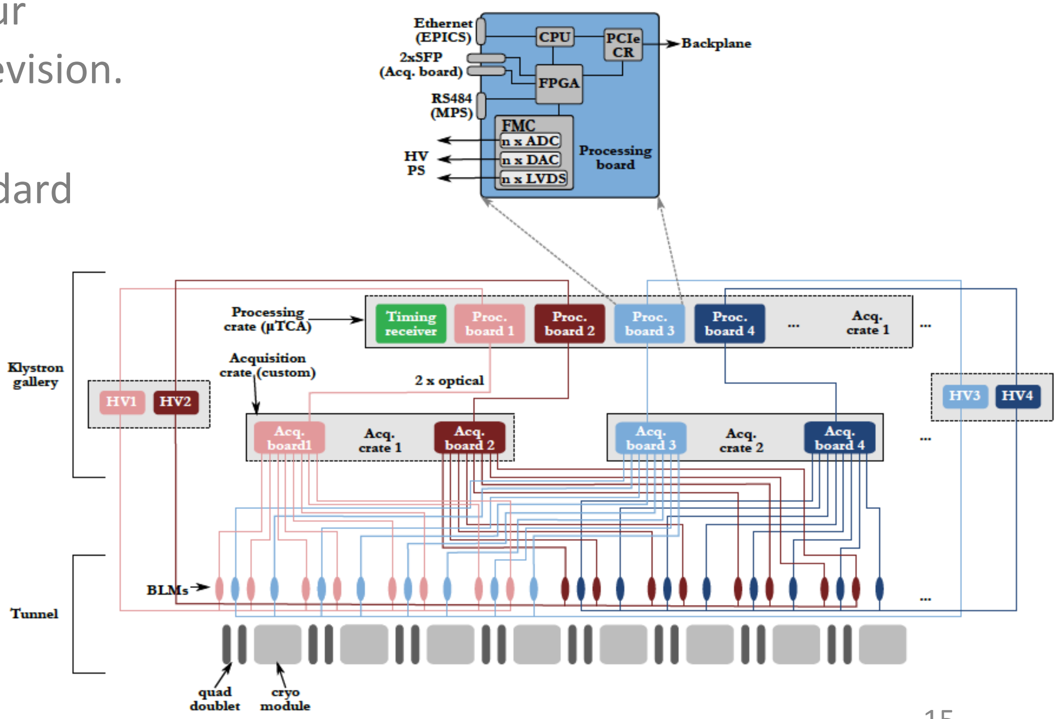


- Plan to determine these fluxes with a use of a Monte Carlo code in the near future.

BLM conceptual design – SCL (1/2)

Current concept for electronics (for ICs):

- Consist of 2 separate units:
  - The BLEDP card (developed for the new BLM system at CERN injector complex) as an **Acquisition Unit**, serving as analogue front-end & digitizer.
  - The BLEDP has a wide dynamic range (10pA – 200mA) - likely to fit our dynamic range even after the revision.
  - Followed by a **Processing Unit**, which is planned to be the standard board provided by ICS division, equipped with FPGA(s) and the interfaces to BIS and EPICS.
- 8 ICs interleaved, connected to 1 Acq. unit (2 optical links), 2 Acq. units in 1 rack.
- 1 Proc. Unit is processing signals for 1 Acq. Unit.

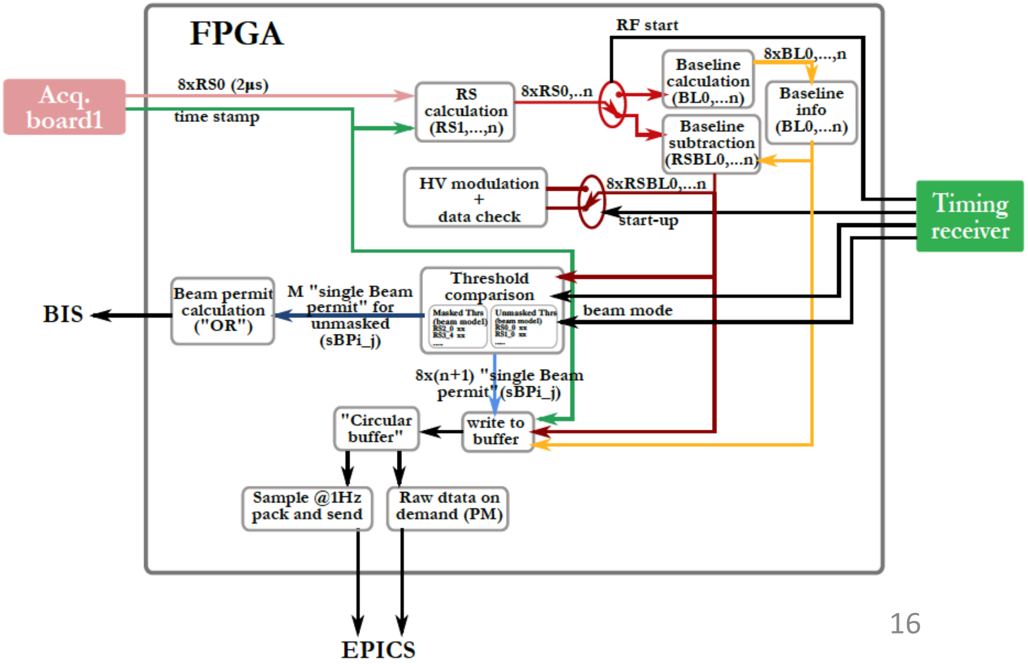


BLM conceptual design – SCL (2/2)

- The Acq. Unit provides the information on the integrated loss over a fixed time (2μs) – **Running Sum 0 (RS0)**.
- Proc. Unit is expected to provide additional RSs giving information on losses integrated over **longer time scales**.
- Current suggestions for RSs based on the list of expected beam modes (5μs, 50μs, 2.86ms):

  RS0-8: 2μs, 4μs, 10μs, 100μs, 500μs, 1ms, 500ms, 1s.

- Due to background from cavities, the Proc. Unit needs to acquire the **baseline** when RF is on and no beam Is in (preferably just before the beam pules) and subtract that from the raw data.
- Depending on the beam mode each RS for each channel can be **Masked** if needed.
- Beam permit is determined by **AND-ing** (all have to be "OK") all (unmasked) RSs for all channels - at least initially.



Summary

- Presented current strategy for monitoring the beam with BLMs:
  - ICs will be used as the primary detectors in SC parts. Presented current conceptual design for the part of the BLM system based on ICs.
  - Photon background from cavities might be a concern for IC based BLMs - plan to investigate an option to use a Cherenkov detectors (or to at least to use the dual photon readout WS system as BLM) in addition to ICs.
  - Investigating the option to use micromegas detectors as neutron detectors in the NC parts of the linac.
- Near future work mostly connected to Monte Carlo simulations (dynamic range, threshold determination, placement of detectors).
- Necessary to have better understanding of beam loss scenarios in order to be able to fully address these issues.

References

[1] see talk by A. Nordt or A. Nordt, “*Beam Instrumentation interfaces to protection systems*”, TAC12, https://indico.esss.lu.se/indico/event/315/session/9/contribution/32/material/2/1.pptx

[2] L. Tchelidze, “*How Long the ESS Beam Pulse Would Start Melting Steel/Copper Accelerating Components?*” ESS/AD/0031, http://docdb01.esss.lu.se/DocDB/0001/000168/001/Time_Response_Requirements_BLM.pdf

[3] B. Cheymol, *“High power and high duty cycle emittance meter for the ESS warm linac commissioning”*, ESS-0038060

[4] Thom Shea privatecommunication

[5] see talk by M. Munoz or M. Munoz, *“Description of Modes for ESS Accelerator Operation”*, ESS-0038258

[6] M. Eshraqi et al. “*Preliminary study of the possible failure modes of the components of the ESS* linac”, ESS-0031413

[7] M. Stockner, *“Beam loss calibration studies for High energy proton accelerators”*, PhD thesis

[8] M. Hodgson, *“Beam loss monitor design investigations for particle accelerators”*, PhD thesis

[9] B. Cheymol, *“ESS wire scanner conceptual design”*, ESS-0020237

[10] M. Stockner et al, “*Classification of the LCH BLM ionisations chamber*”, Proc. Of DIPAC 2017

[11] B. Cheymol, “*Proposal for a scintillator readout prototype”*, ESS-0033505

[12] Micromegas team (T. Papaevangelou, A. Delbart, G. Tsiledakis, J. Morroncle) from CEA Saclay, *“Preliminary simulations for micromegas used as BLM”*, report received through internal discussions

[13] E. Donoghue et al, *“Studies of electron activities in SNS-type SC RF cavities”*, Proc. Of 12th Int. Workshop on RF Supercondictivity, Cornell Univ., USA

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Back up material (I)

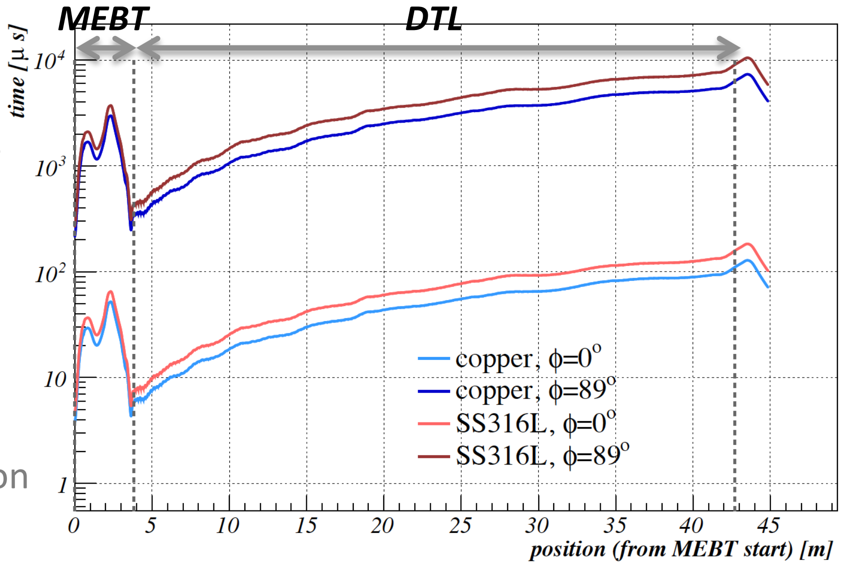
Response time (1/2)

- Time response requested by machine protection [1]:
  - In NC linac: ~1 μs.
  - In SC Linac: ~10 μs.
  - Based on a simplified melting time calculations when a uniform beam hits a block of material under rectangular incidence [9].

- Rechecked the calculations with updated parameters. Assumptions:
  - Proton beam with a Gaussian profile (instead of uniform) and 62.5mA current (instead of 50mA) hits a block of material under perpendicular (Φ=0°) or shallow (Φ=89°) incident angle.
  - Calculated time to reach the melting point in the volume bin with highest temperature (see next page).
  - Highest temperature under constant irradiation expected in a small small volume of material around the Bragg peak.
  - No cooling.
  - SRIM calculations used to estimate energy deposition at the Bragg peak.

Response time (2/2)

- Observations – NC linac
  - Time to melt strongly depends on incident angle and reaches below 5μs at the beginning of the MEBT – need for revision of the 1μs limit in NC linac?
  - Not that a simplified model used for the estimation, no cooling processes.
  - Conductive cooling might be efficient for a thin layer
  - Also: the worst case scenario with full beam at perpendicular incidence is expected only when the valve enters the beam. The primary layer of protection for this case is expected to be the Local Protection system.

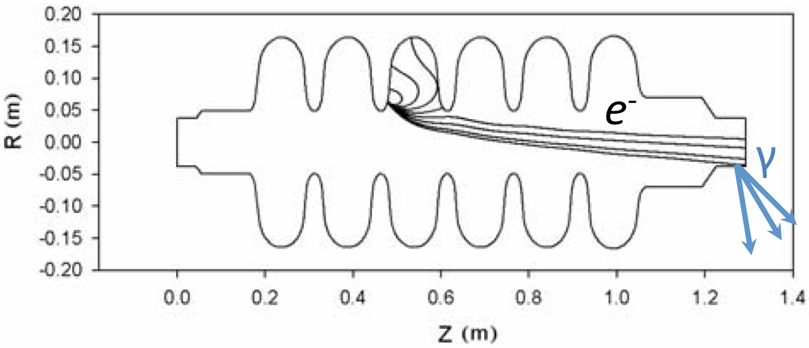


Time needed to reach melting temperature with beam parameters expected along the MEBT and DTL

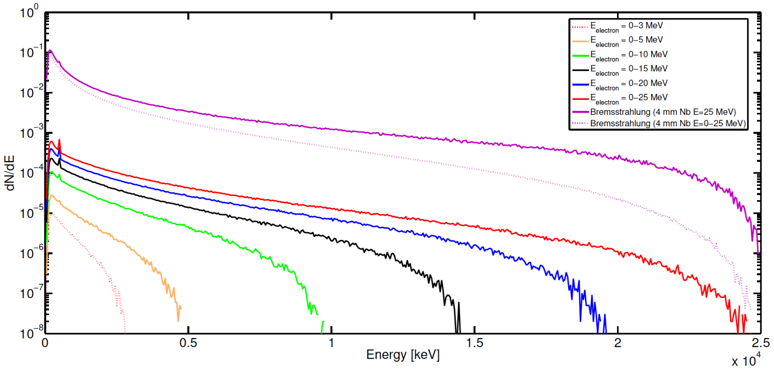
- Observations – SC linac
  - Calculated time to melt ~100μs at the beginning of the SC parts – fits with the 10μs response time limit set for the SC linac.
- However, experience at SNS raises a concern:
  - Degradation of cavities observed at SNS after loosing ~20μs pulse of 26mA beam ~10/day [4]
  - Do we need to be faster in order to detect this type of events in time?

Background photons due to RF cavities

- Photon background due to the RF cavities mainly due to field emission from electrons from cavity walls, resulting in bremsstrahlung photons created in the field of nuclei of cavity/beam pipe materials [13].



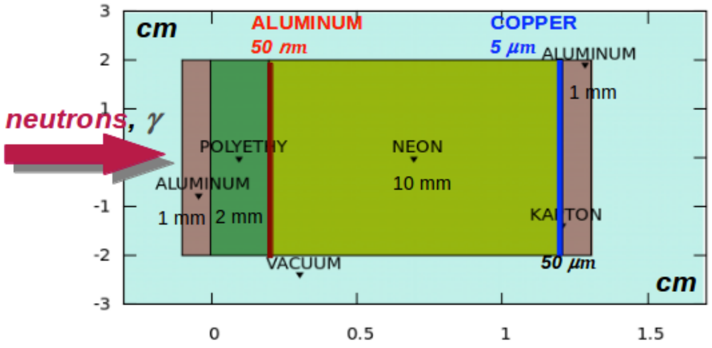
- Energy spectra estimations show that photons up to few tens of MeV can be expected [9]:
  - A MC code (FLUKA) was used for these estimations where a pencil electron beam is impacting a 4mm niobium foil.
  - Purple curves on the plot on the left show expected energy spectra for the photons produced at the exit of the foil:
    - Solid line – for the monochromatic beam of electrons with energy of 25MeV
    - Dotted line – for the beam of electrons with uniform energy distribution from 0 to 25MeV.
    - Spectra are normalised per number of primaries.
  - Note: maximum acc. Gradient expected at ESS ~25MeV/m, cavity size ~1m.



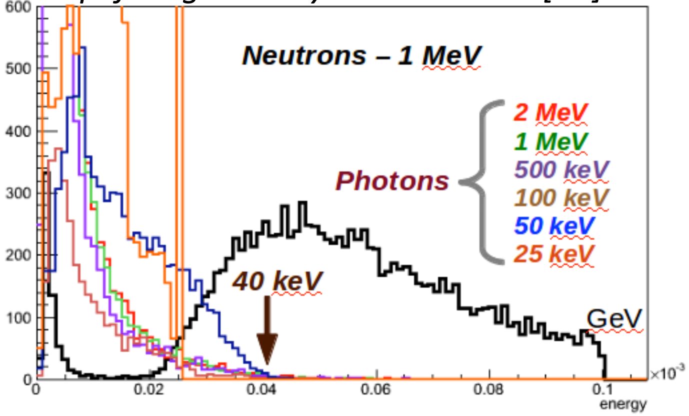
Micromegas as neutron sensitive BLM

- Such a BLM should consist of
  - Thin foil of "heavy" material to stop the X-rays (Al, Fe, SS,…).
  - Followed by a layer of proton rich material (CH_2), sensitive to fast neutrons, which are scattered on hydrogen atoms, producing protons easy to detect with micromegas.
- The discrimination between fast neutrons is based on their difference in the energy deposition in gas.
- Different neutron conversion materials could be used in order to be sensitive to thermal neutrons as well. It would be also possible to have a detector with 2 segments, one for fast neutrons and other for thermal ones (B^{10} based conversion material).

From [12]



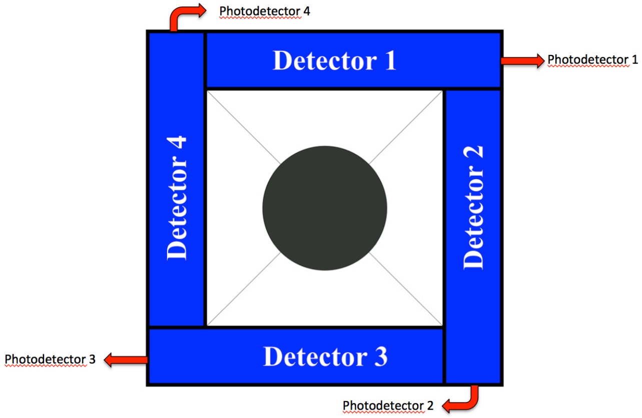
Example of simulated p (from 1MeV n) and γ energy deposition spectra in the simplified geometry shown above [12]



Photon based dual readout for WS system & BLM (1/2)

WS system at high energies

- For proton energies > 200 MeV, SEM current is to low for profile measurements, while flux of secondaries produced on the wire are energetic enough to cross the vacuum chamber.
- The idea is to use this secondaries and detect them with a "ring" of 4 scintillator rods placed around the beam pipe downstream of the wire.
- The light could be collected with a photodiodes attached to one scintillator ends.
- In order to avoid the background from the cavities (when they are on) a dual readout is currently under investigation:
  - Light from the scintillator can be collected with a photodiode.
  - A WLS fiber can used to produce and transport Cherenkov photons to a photodetector.
  - A groove for placing the fiber can be machined in the scintillator.
  - The scintillating material should have a the emission peak (BGO, ~500nm), which does not match the absorption peak of the fiber (eg. Kuraray B# ~350nm).
  - Details on alternative geometry in [11].



Photon based dual readout for WS system & BLM (2/2)

Dual readout as part of BLM & WS systems

- The data from the dual readout can additionally serve for BLM purposes.
- The idea is to use the WLS fiber as a BLM detector during normal operation (no wire in the beam) in addition to its functionality for the WS system during profile measurements.
- Plan to do series of Monte Carlo simulations in order to see if this fiber can serve as a BLM and to optimize the design (geometry/ placement of the fiber, materials).
- This WS system is planned to be used for beam energies above 200MeV, 3 devices in Medium and 1 in High β section.
- Depending on the out come of the study there is a possibility to increase the number of these devices.

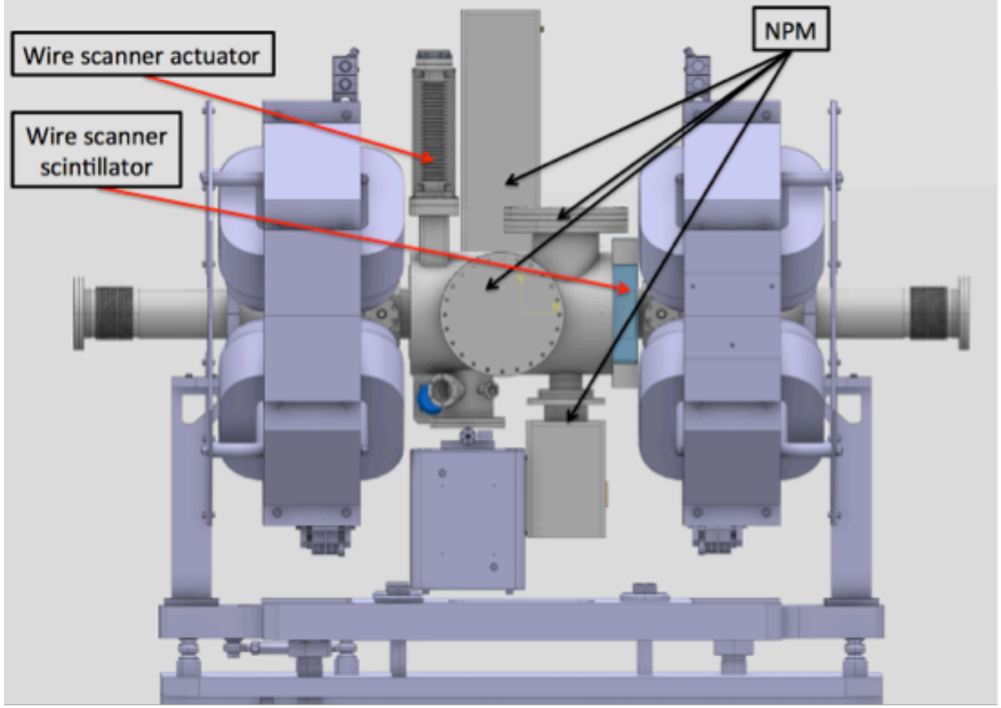
Back up material (II):

Dual readout for the WS system – more detailed description

(by Benjamin Cheymol)

Introduction

- Above ≈200 MeV, the secondary emission might be too weak to reconstruct the beam profile.
- The reconstruction can be done by measuring the shower created in the wire.



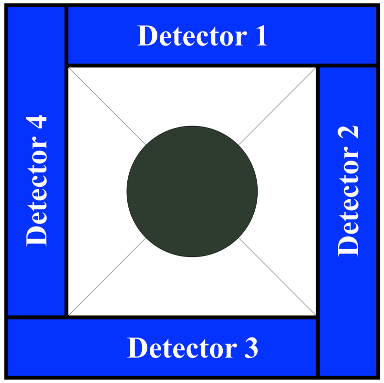
Preliminary layout of a typical Linac Warm Unit (LWU) foreseen to be installed in the elliptical and HEBT section.

Scintillator can be seen as a Calorimeter, light collection efficiency must be known and optimized in order to defined the acquisition electronic.

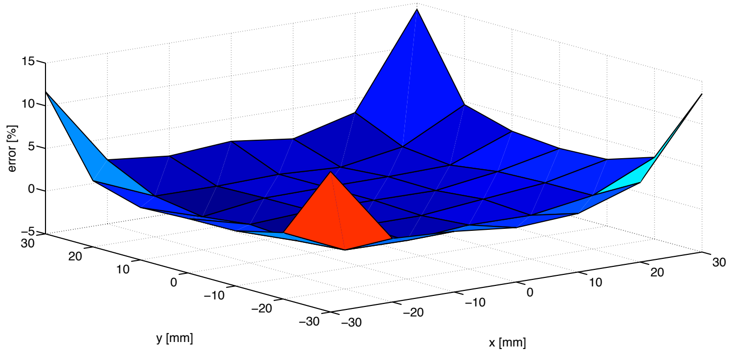
Cavities background might be an issue.

Detector - first simulations

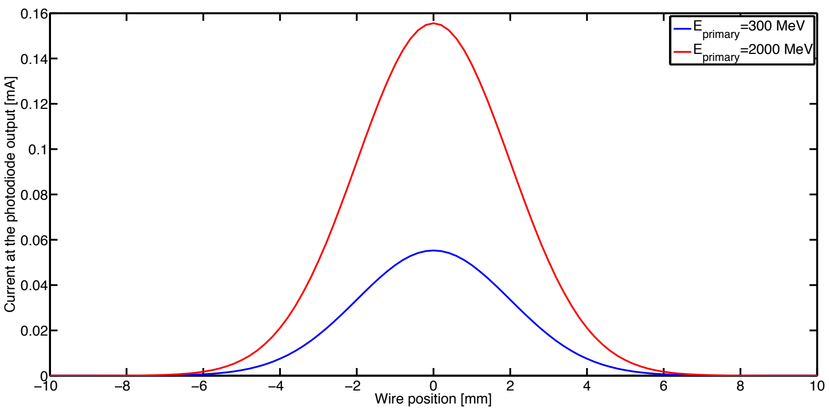
- Detection of hadronic shower created by the wire
  - Monte Carlo simulation on going
  - Detector:
    - BGO crystal + photodiode
    - BGO crystal + silicon APD
- Gamma background might be an issue



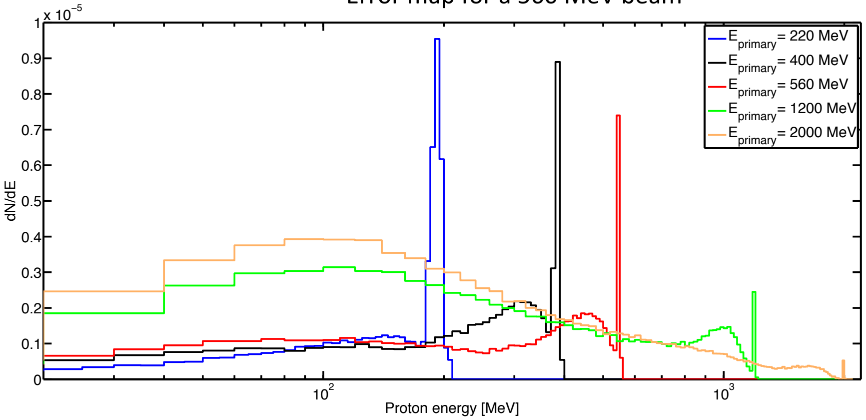
Detector geometry, in blue the scintillators and in black the beam pipe, the diameter of the beam pipe is 100



Error map for a 560 MeV beam



Estimated signal at the output of a typical photodiode coupled with a BGO scintillator, assuming 2% light collection efficiency.



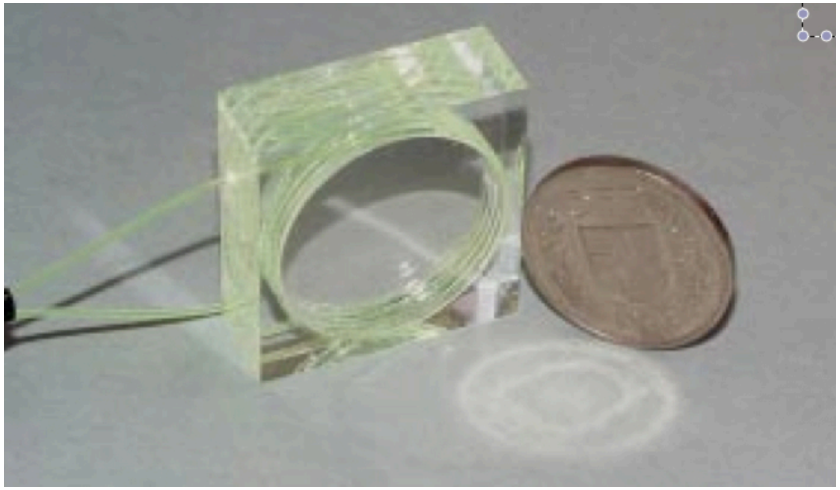
Energy spectrum of proton reaching the detector surface.

Light collection

- Several option
  - Direct readout with a photodiode
    - Light collection ≈40%
    - Signal ≈ mA range
  - Coupling with a WLS fibre
    - LSO crystal or plastic scintillator
    - Si APD or PMT (depending on light power on the photodetector)
    - Light collection ≈1%
  - Detection of Cerenkov light
    - In case of background due to cavities
    - Direct connection of PMT or with WLS fibre
- Simulation and prototyping phase needed
  - Estimation of light collection efficiency
  - Test in RF bunker with ESS cavities
  - Possibly test with beam

Ideas for simulations/prototypes

- BGO crystal with a direct photodetector coupling.
- BGO crystal with a direct photodetector coupling and a WLS fiber(s) for Cherenkov detection
- A quartz plate with a WLS fiber for Cherenkov detection
- Plastic scintillator and/or LSO crystal with a single straight WLS fiber
- Plastic scintillator and/or LSO crystal with a single WLS fiber positioned like the LHCb PSD.



LHCb PSD prototype (plastic scintillator and WLS fiber)

Proposal for the upgrade of CMS Hadronic EndCap Calorimeter (quarts plate and UV fibers)