Status of baseline ECAL module design and additional options

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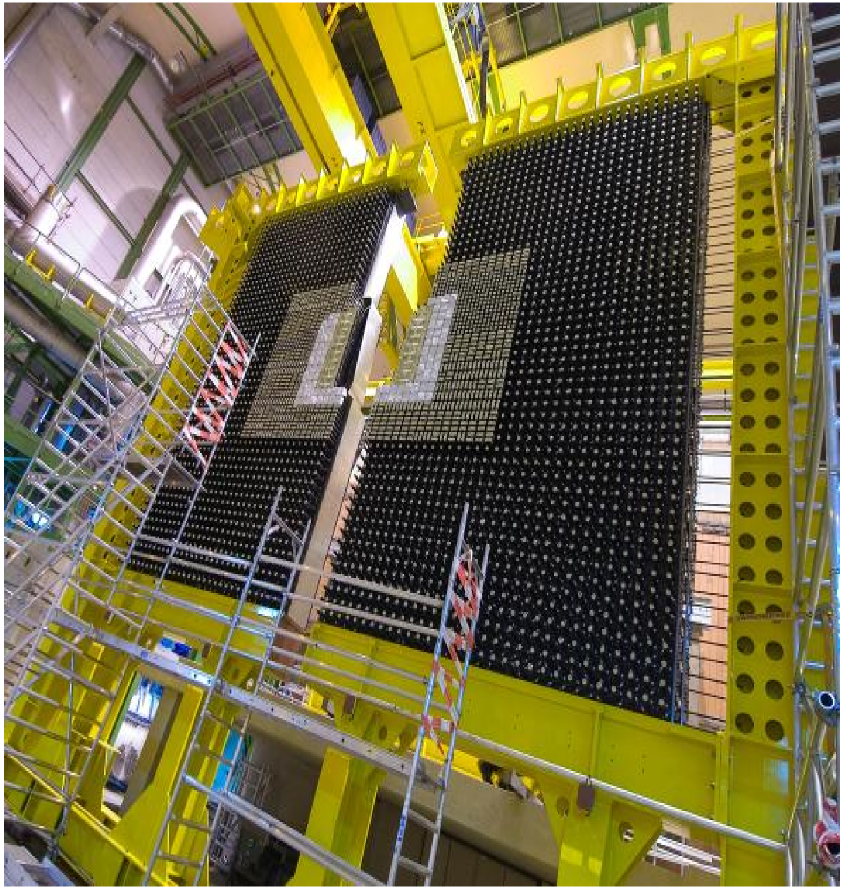
CERN LHCb CRYSTAL CLEAR EP R&D

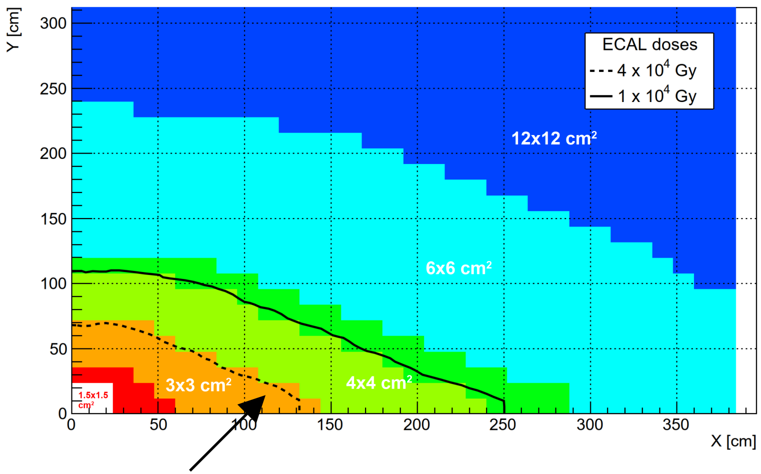
ECAL Upgrade II Workshop
Orsay, 12/12/2022



Reminder: Baseline configuration for Upgrade II

5 ECAL regions matching the radiation maps:

Cell size:	Modules:
1.5 x 1.5 cm^2	32 *new* modules for extreme conditions of up to 1 MGy
3 x 3 cm^2	144 *new* modules with "moderate" radiation requirements of up to ≈ 200 kGy
4 x 4 cm^2	272 *new* modules + 176 refurbished existing modules (add long. segmentation?)
6 x 6 cm^2	896 rebuilt + 448 refurbished existing modules (add long. segmentation?)
12 x 12 cm^2	1'344 refurbished existing modules (add long. segmentation?)



Radiation limit of current Shashlik technology

Number of channels:
Current ECAL: 6'064 cells (6'016 channels read)
Full double-sided readout (long. segmentation):
30'208 channels

The SpaCal modules need to be tiled to meet the energy resolution target

Downscoped variant: double-sided readout only for the SpaCal modules

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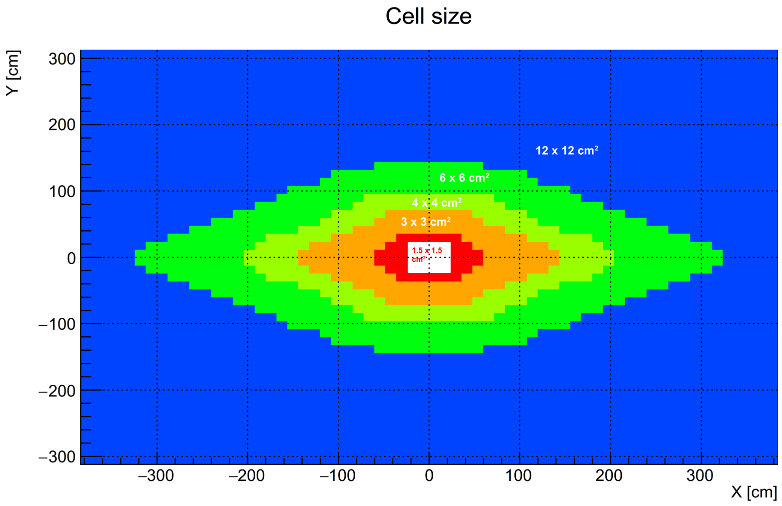
Reminder: LS3 configuration



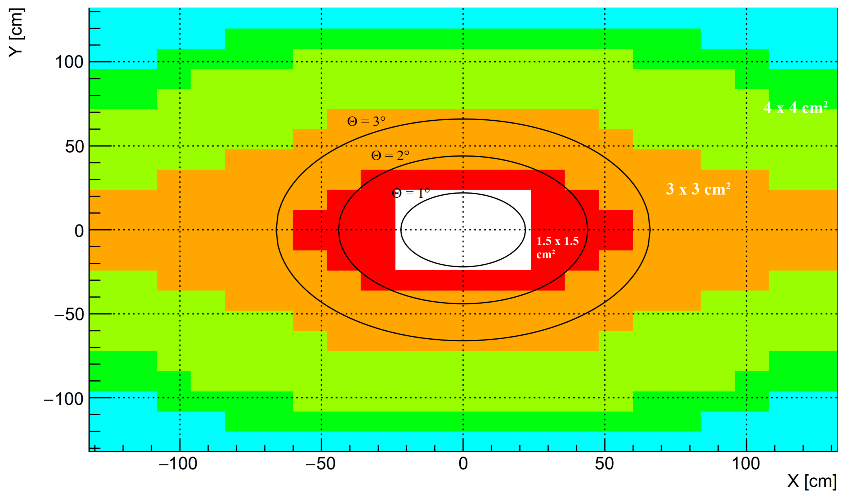
- 9’344 cells (compared to 6’064 in current ECAL)
- Timing will be implemented for SpaCal region
→ requires new electronics for ≈ 3’300 cells
- Existing modules will be rearranged
(4x4 cm^2 Shashlik modules moved out to avoid too much radiation damage, WLS fibres could be easily replaced)

Cell size:	Modules:
2 x 2 cm^2	32 *new* SpaCal-W modules
3 x 3 cm^2	144 *new* SpaCal-Pb modules
4 x 4 cm^2	176 existing modules in rhombic configuration
6 x 6 cm^2	448 existing modules in rhombic configuration
12 x 12 cm^2	2’512 existing modules in rhombic configuration

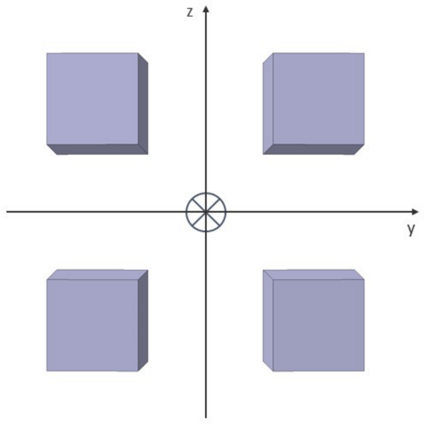
Rotation of SpaCal modules

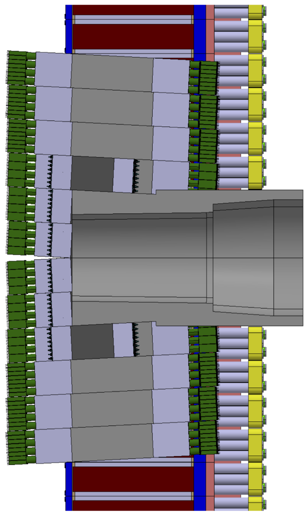
• To avoid inhomogienities in the sampling, an incidence angle with respect to the beam direction is needed for SpaCal
→ 3° in the X and Y directions sufficient to meet energy resolution target

Inner region of the LS4 baseline:



→ Incidence angle for photons from IP, θ, not sufficient





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→ Tilt of SpaCal modules implemented in the detector design (mechanical stability) and simulation software

- Baseline SpaCal modules
- Baseline Shashlik modules
- Additional options

Basic SpaCal modules types

Absorber	Tungsten (W)		Lead (Pb)
Installation	LS3	LS4	LS3 / LS4
Fibres	**Polystyrene**	**GAGG**	**Polystyrene**
Cell size	2 x 2 cm^2	1.5 x 1.5 cm^2	3 x 3 cm^2
Molière radius	1.8 cm	1.46 cm	≈ 3 cm
Radiation length	0.72 cm	0.62 cm	≈ 1 cm
Long. sections	1 (19 cm)	2 (4.5 cm + 10.5 cm)	1 (29 cm) / 2 (8 cm + 21 cm)

- Three basic module types: polystyrene fibres replaced by GAGG fibres in W absorber during LS4
- Longitudinal segmentation during LS4: transition at shower maximum for 20 GeV electron / 10 GeV photon

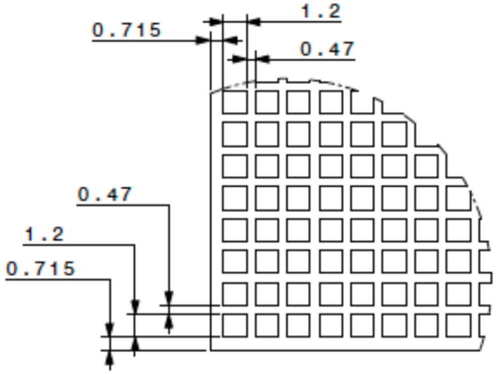
Design considerations:
- Cell sizes defined by occupancy
- Molière radii tuned (by choice of materials and geometry) to match the cell size

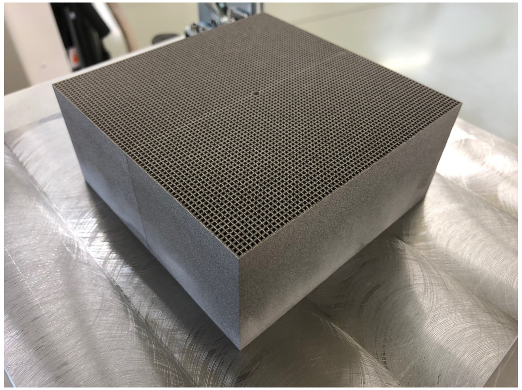
→ sizeable charge sharing: excellent position resolution (in the order of 0.5 - 2 mm)
- Module length large enough to keep longitudinal leakage tiny (at least 25 radiation lengths)

Looking closer...

Modules with W absorber:
• The same absorber can be used with polystyrene (LS3) or GAGG (LS4) fibres
→ square fibres for technical reasons (production of GAGG fibres)

Fibre size: 1.0 x 1.0 mm²
Dimension of the holes: 1.2 x 1.2 mm²
Pitch: 1.67 mm
Absorber wall thickness: 0.47 mm
→ 5041 holes per module

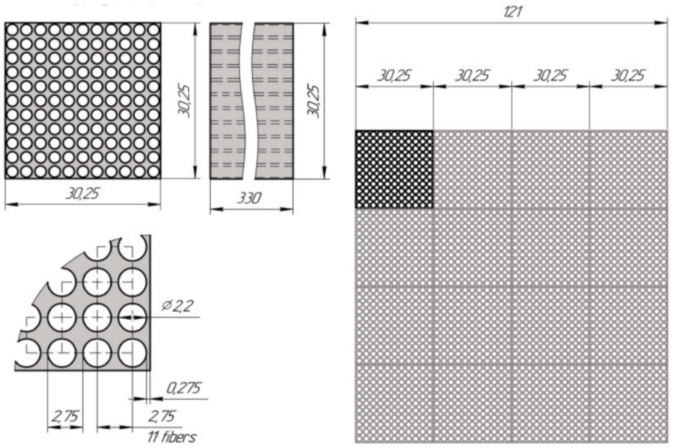




Modules with Pb absorber:
• Larger round fibres due to technical advantages

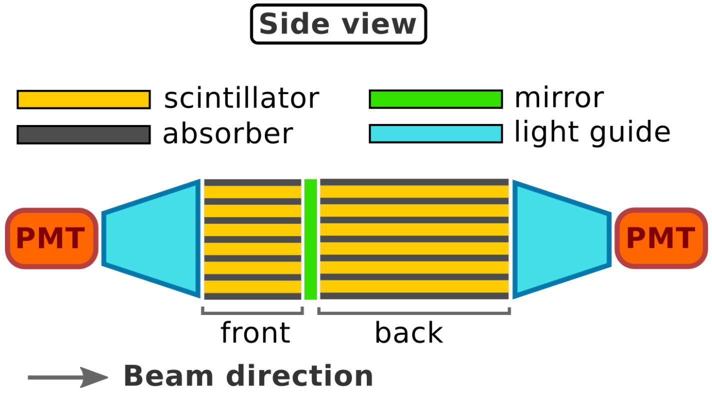
Fibre diameter: 2.0 mm
(found sufficient for energy resolution)
Hole diameter: 2.2 mm
Pitch: 2.75 mm
→ 1936 holes per module

→ see talk by Sergey Kholodenko



→ see talk by Hubert Gerwig

Motivations for longitudinal segmentation



- Improved time resolution from combination of front and back section (complementary information)
→ see talks in the test beam results session

- Less effect from radiation damage on performance (less impact on constant term in energy resolution)
→ see talk by Marco Pizzichemi

- Additional information in event reconstruction (e.g. better separation of close-by photons from high-energy neutral pions)
→ see talk by Alexey Boldyrev

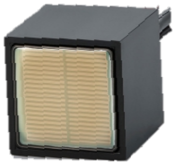
- Potential improvements to particle identification, in particular electron-hadron separation
→ see session on Friday morning

Other technical design aspects

Photon detectors:

Key characteristics to be met at required gains:
- Time resolution
- Signal linearity over full energy range
- Energy resolution

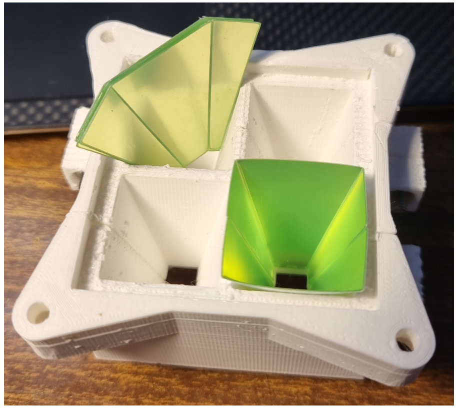
PMTs currently under investigation (also in test beams):
R7600U-20, R11187 (TileCal), R14755U-100, FEU115M (Russian)

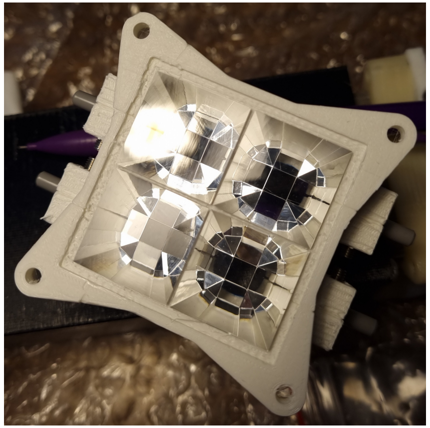


→ Ideal situation would be to use the same PMT for both SpaCal regions (most cost effective)

→ see talk by Edu Piacoste

Light guides:





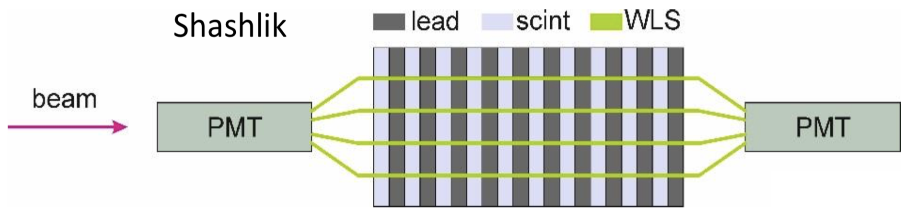
Hollow light guides coated with reflective material (focus of recent test beams)
→ Intrinsically radiation hard
→ Most cost effective solution

→ see talk by Matteo Salomoni

- Baseline SpaCal modules
- Baseline Shashlik modules
- Additional options

Shashlik modules for Upgrade II

Shashlik modules: 4 mm thick scintillating tiles and 2 mm thick lead absorber tiles with wavelength shifting (WLS) fibres



• Molière radius: 3.5 cm

• Radiation hardness limit is 40-50 kRad
→ suitable for periphery of ECAL (≈ 94% of area)

• WLS fibres can be replaced without disassembling the modules (already done for prototypes)

• Baseline for LS4 is double-sided readout with continous fibres:
study of current and optimised modules ongoing
→ see presentation by Yuri Guz

Options under consideration:
• Split WLS fibres with reflective material between front and back sections
• Use of radiation harder WLS fibers in the inner part, faster WLS fibers in the outer part (where the typical particle energies are lower)

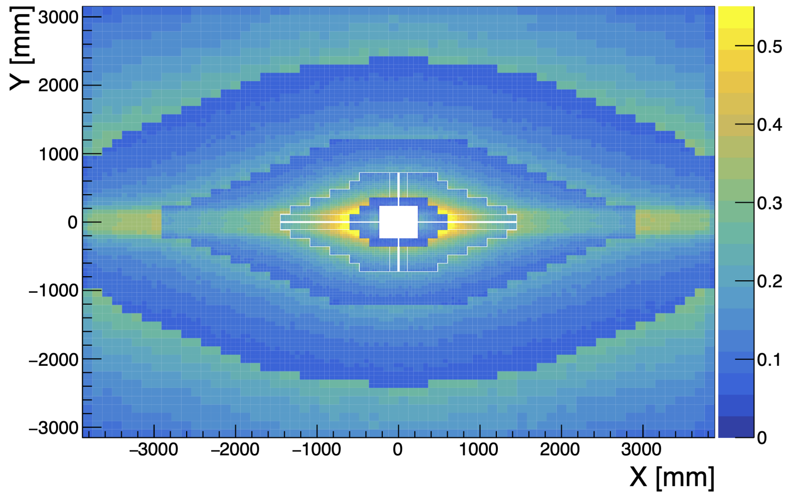
- Baseline SpaCal modules
- Baseline Shashlik modules
- Additional options

Intermezzo: occupancies

- Andreas showed in the previous talk the EM flux (= electrons and photons per BX and cell)
- Here occupancy from detailed simulation (→ see talk by Marco Pizzichemi) of the modules described of the previous slides (also including the hadronic component!)

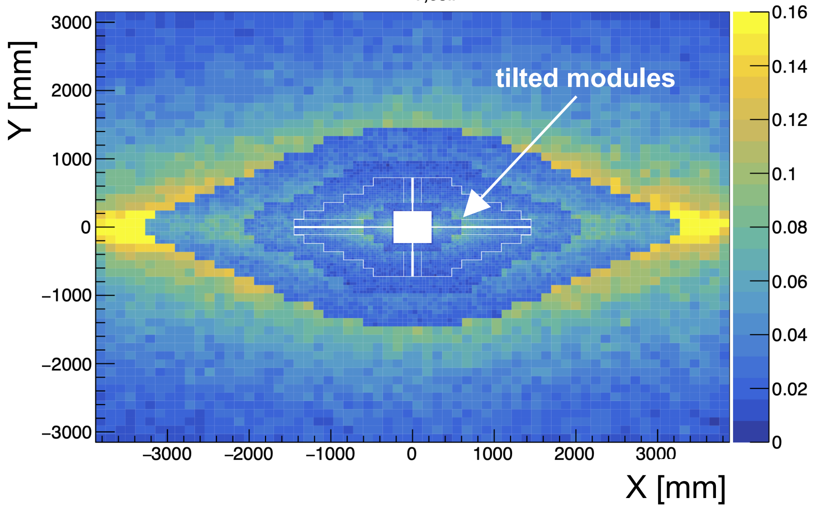
LS4 (1.5 x 10^{34} $cm^{-2}s^{-1}$):

Occupancy, front section, $E_{T,cell}$ > 25 MeV



LS3 (2 x 10^{33} $cm^{-2}s^{-1}$):

Occupancy, $E_{T,cell}$ > 50 MeV



- No timing information used
- Generally the occupancy maps are reasonably flat
- High occupancy directly outside of SpaCal region with W absorber, impact also seen in physics benchmarks

Options to refine the baseline design

LS3 configuration:

• In addition to timing foreseen in the SpaCal region, add timing capabilities to (a part) of the Shashlik region
→ would require new electronics for more channels in LS3

LS4 configuration:

• Mitigation of high-occupancy region around the inner 32 modules:
- Use ≈ 40 instead of 32 SpaCal-W/GAGG modules?
→ Absorber largely available, because SpaCal-W/GAGG modules are shorter than SpaCal-W/Poly
- Add additional SpaCal-W/Poly region?
→ Move LS3 modules outside and add new SpaCal-W/GAGG modules for LS4

• Build more than 144 SpaCal-Pb/Poly modules instead of new Shashlik modules with 4x4 cm^2 cell size?
→ depends on which solution is more cost effective and the interest of the involved institutes

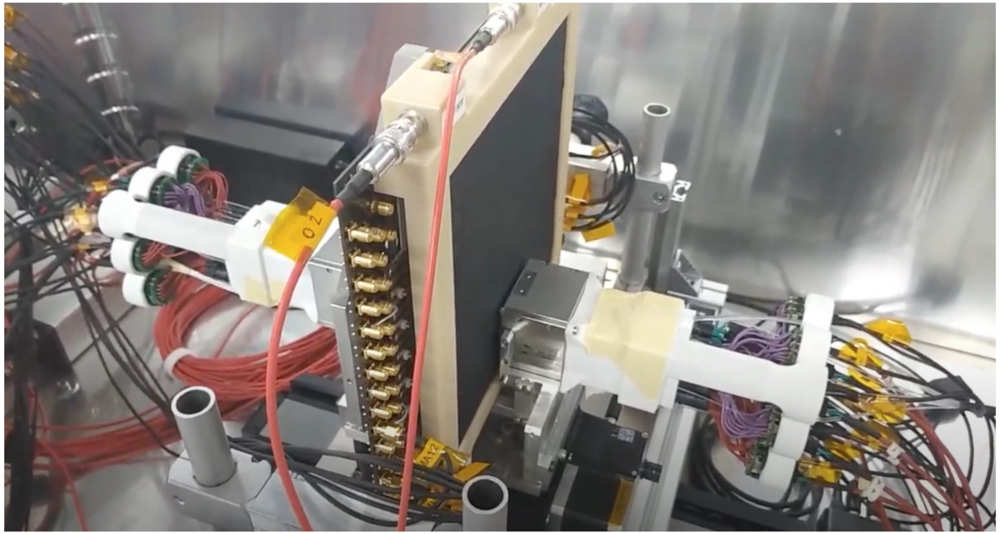
→ Physics impact of these modifications to be studied

Additional layers for LS4 (1)

Alternative options described in the Framework TDR:
• Timing layer in the shower maximum (MCP-PMTs or silicon layers)
→ benefit over baseline modules to be demonstrated
• Tungsten-silicon sampling calorimeter (but: expected energy resolution is ≈20% / $\sqrt{E} \oplus 1\%$)

Current studies:

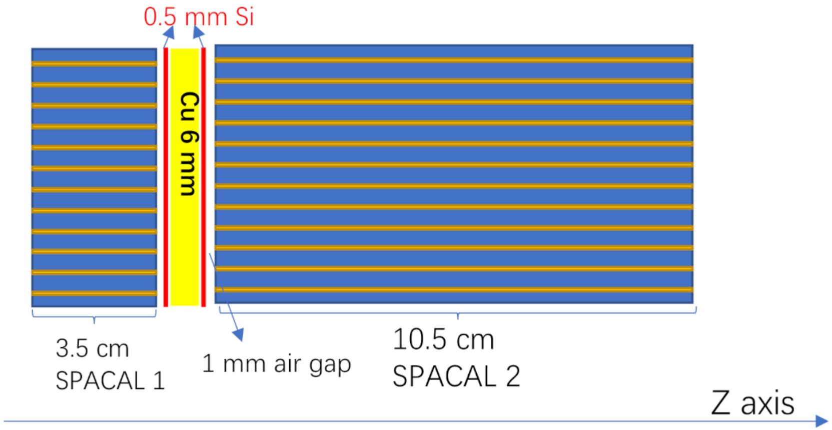
1.) Active R&D on LAPPD timing layer
(including test beams with SpaCal-W/GAGG module, irradiation campaigns)
→ see talk by Stefano Perazzini



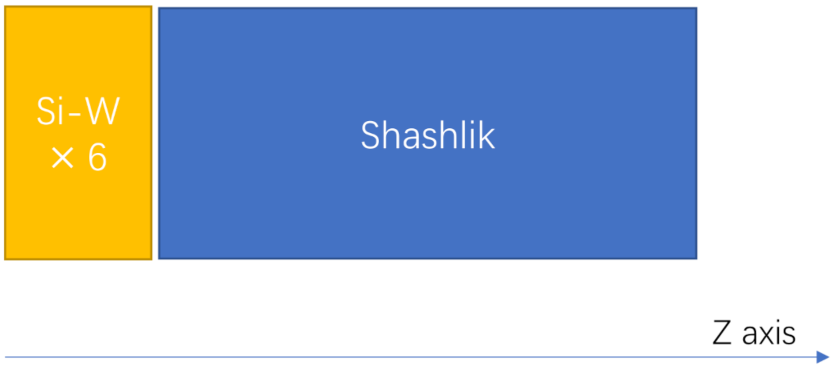
Additional layers for LS4 (2)

2.) Simulation studies of additional silicon layers

SpaCal-W/GAGG with 2 included silicon timing layers



Si-W pre-shower detector in front of Shashlik module



→ see talk by Zhenwei Yang

Summary and conclusions

- Consolidation during LS3 needed to ensure survival of the ECAL:

- Addition of radiation-tolerant SpaCal region
- Rearrangement of Shashlik modules for better physics performance

- Design of SpaCal-W and SpaCal-Pb modules with polystyrene fibres established

→ These modules and the related infrastructure (electronics platform, …) are also useful for Upgrade II

- No show stoppers known, but large amount of R&D needed before mass production

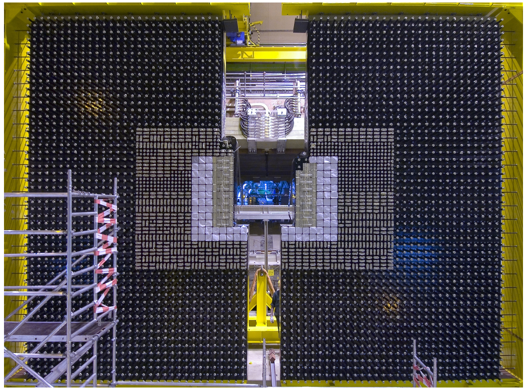
- In parallel, the work towards Upgrade II continues:

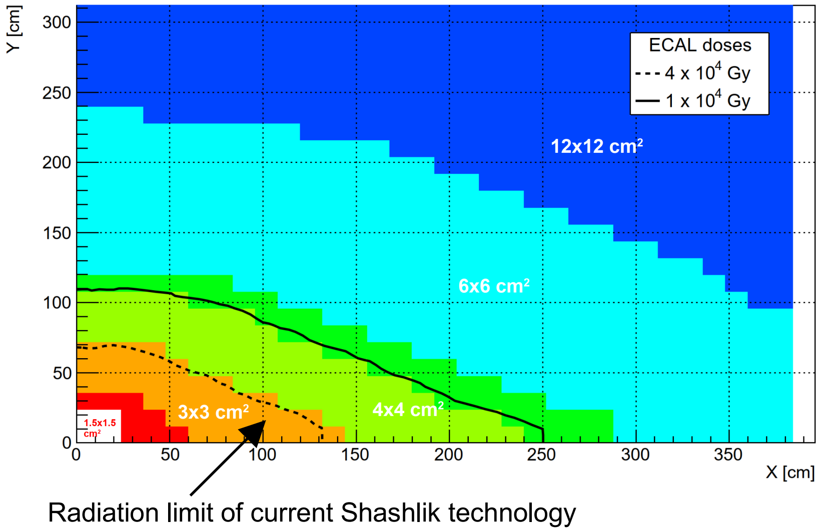
- Optimisation of the LS4 configuration through detailed simulations
- R&D on crystal scintillator for the innermost region
- Improvements to the timing capabilities of Shashlik modules
- R&D on the timing layer option
- …

Thank you!

Backup slides

Reminder: SpaCal/Shashlik ECAL for Upgrade II





Requirements for the Upgrade II:

- Sustain radiation doses up to 1 MGy and ≤ 6 x 10^{15} 1 MeV neq / cm^2 in the centre
- Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
- Pile-up mitigation crucial

→ Timing capabilities with O(10) ps precision, preferably directly in the calorimeter modules

→ Increased granularity in the central region with denser absorber

SpaCal technology for inner region:

- Innermost modules with scintillating crystal fibres and W absorber

→ Development of radiation-hard scintillating crystals

→ 1.5x1.5 cm^2 cell size

- 40-200 kGy region with scintillating plastic fibres and Pb absorber

→ Need radiation-tolerant organic scintillators

→ 3x3 cm^2 cell size

Shashlik technology:

- Timing with new WLS fibres, long. segmentation (double-sided readout)

→ Cost optimisation by refurbishing ≈2000 existing modules for timing

→ Adapt to the required cell sizes by adding ≈1300 new modules

LS3 consolidation: W absorber for innermost modules equipped with scintillating plastic fibre for 2x2 cm^2 cell size

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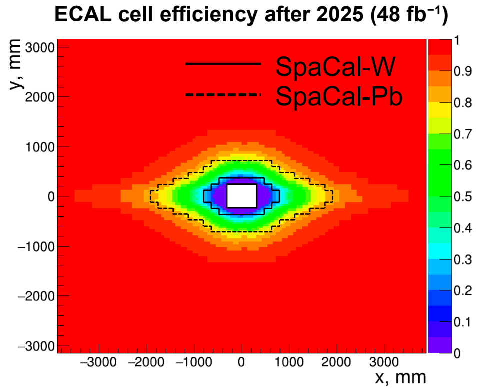
Reminder: LHCb ECAL upgrade strategy



Run 3 in 2022-2025:
Run with unmodified ECAL Shashlik modules at L = 2 x 10^{33} $cm^{-2}s^{-1}$

LS3 consolidation in 2026-2028:
Introduce single-section rad. tolerant SpaCal (2x2 and 3x3 cm^2 cells) in inner regions and rebuilt ECAL in rhombic shape to improve performance at L = 2(4) x 10^{33} $cm^{-2}s^{-1}$
→ 32 SpaCal-W & 144 SpaCal-Pb modules with plastic fibres compliant with Upgrade II conditions
→ Could include timing information with single-sided readout to inner regions

LS4 Upgrade II in ≥2035:
Introduce double-section rad. hard SpaCal (1.5x1.5 & 3x3 cm^2 cells) and improve timing of Shashlik modules for a luminosity of up to L = 1.5 x 10^{34} $cm^{-2}s^{-1}$
→ Innermost SpaCal-W modules equipped with crystal fibres
→ Include timing information and double-sided readout to full ECAL for pile-up mitigation